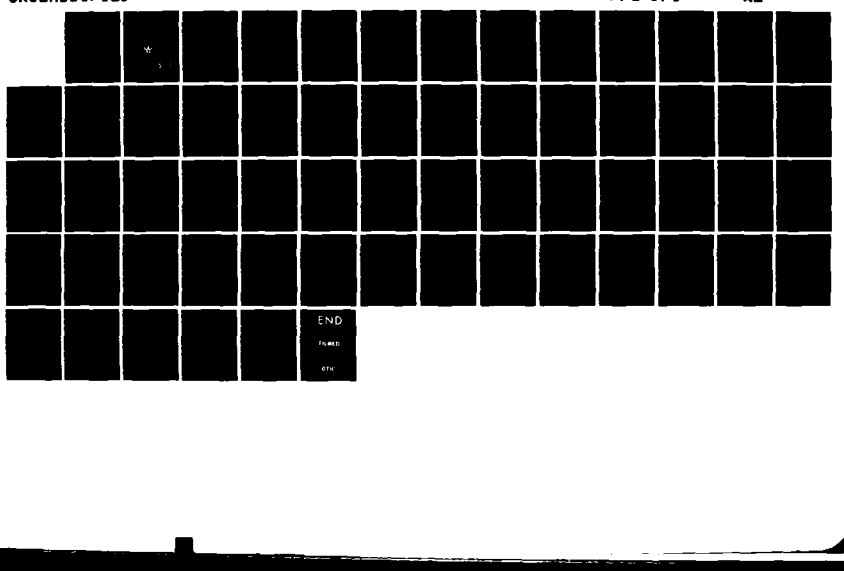
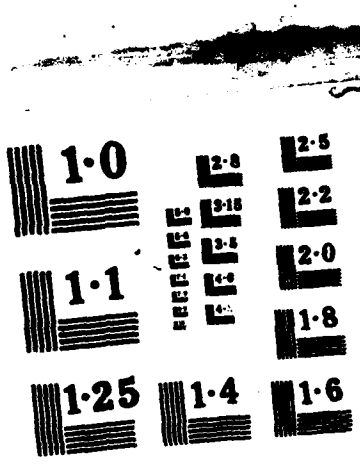
AD-A154 348 JOINT SERVICES ELECTRONICS PROGRAM(U) HARVARD UNIV 1/1
CAMBRIDGE MA DIV OF APPLIED SCIENCES M TINKHAM
31 MAR 85 N00014-84-K-0465

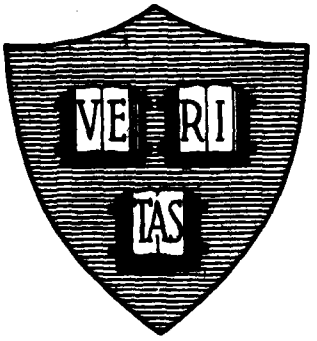
UNCLASSIFIED F/G 9/5 NL




1·0
1·1
1·25
2·8
3·15
3·5
4·0
2·5
2·2
2·0
1·8
1·4
1·6

Division of Applied Sciences
Harvard University Cambridge, Massachusetts

ANNUAL PROGRESS REPORT NO. 98



JOINT SERVICES ELECTRONICS PROGRAM
N00014-84-K-0465

Covering Period
April 1, 1984 - March 31, 1985

March 1985

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Annual Progress Report No. 98	2. GOVT ACCESSION NO. AD-A154 348	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) JOINT SERVICES ELECTRONICS PROGRAM Progress Report		5. TYPE OF REPORT & PERIOD COVERED Annual April 1, 1984-March 31, 1985 6. PERFORMING ORG. REPORT NUMBER Report No. 98
7. AUTHOR(s) M. Tinkham		8. CONTRACT OR GRANT NUMBER(s) N00014-84-K-0465
9. PERFORMING ORGANIZATION NAME AND ADDRESS Division of Applied Sciences Harvard University Cambridge, MA 02138		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research 800 N. Quincy Street Arlington, VA 22217		12. REPORT DATE March 31, 1985 13. NUMBER OF PAGES 58
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

This document has been approved for public release and sale; its distribution is unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Approved for public release; distribution unlimited.

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Solid state electronics, quantum electronics, information and control electronics, optimization, electromagnetic phenomena.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An annual report of the JSEP (Joint Services Electronic Program) in solid state electronics, quantum electronics, information electronics control and optimization and electromagnetic phenomenon is presented. Results of the research to date are summarized and significant accomplishments are discussed.

Keywords include;

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Joint Services Electronics Program
N00014-84-K-0465

ANNUAL PROGRESS REPORT NO. 98

Covering Period
April 1, 1984 - March 31, 1985

The research reported in this document, unless otherwise indicated, was made possible through support extended to the Division of Applied Sciences, Harvard University by the U. S. Army Research Office, the U. S. Air Force Office of Scientific Research and the U. S. Office of Naval Research under the Joint Services Electronics Program by Contract N00014-84-K-0465. Related research sponsored by the Office of Naval Research, the National Science Foundation, the National Aeronautic and Space Adiministration, and by the University is also reported briefly with appropriate acknowledgment.

Division of Applied Sciences
Harvard University
Cambridge, Massachusetts

ANNUAL PROGRESS REPORT NO. 98

Joint Services Contract

N00014-84-K-0465	The Steering Committee

Related Contracts

N00014-79-C-0419	T.T. Wu
N00014-79-C-0776	Y.C. Ho
N00014-83-K-0030	N. Bloembergen, F. Spaepen
N00014-83-K-0383	M. Tinkham
N00014-84-K-0504	R.W. Brockett
NSF-ECS-81-21428	R.W. Brockett
NSF-ECS-82-13680	Y.C. Ho
NSF-DMR-81-08327	W. Paul
NSF-DMR-82-12189	P.S. Pershan
NSF-DMR-83-16979	P.S. Pershan
NSF-PHY-82-07080	T.W. Mossberg
NSF-INT-83-11841	P.S. Pershan
DAAG29-83-K-0027	R.W. Brockett
DAAG29-83-K-0040	T.W. Mossberg
AFOSR-81-7401	R.W. Brockett
DE-FG02-84-ER-40158	T.T. Wu
SERI XB-2-02144-1	W. Paul

JOINT SERVICES ELECTRONICS PROGRAM

April 1, 1984 - March 31, 1984

ADMINISTRATIVE STAFF

Contract

N00014-84-K-0465

The Steering Committee

Prof. N. Bloembergen
Prof. R.W. Brockett
Prof. H. Ehrenreich
Prof. Y.C. Ho
Asst. Prof. E. Mazur
Asst. Prof. T.W. Mossberg
Prof. W. Paul
Prof. P.S. Pershan
Asst. Prof. R. Suri
Prof. M. Tinkham
Prof. T.T. Wu
Dr. P. McKinney
Dr. L. Strong

RESEARCH STAFF

Dr. H. Akoh
Dr. J. Baillieul
Dr. J.T. deBettencourt
Dr. N. Bloembergen
Dr. B. Bonnard
Dr. R.W. Brockett
Dr. C.I. Byrnes
Dr. X. Cao
Dr. N.W. Carlson
Dr. C.D. Cordero-Montalvo
Dr. M. Deutsch
Dr. H. Ehrenreich
Dr. J.U. Free
Dr. K.C. Hass
Dr. Y.C. Ho
Dr. R.W.P. King
Dr. H. Kurz
Dr. O. Liengme
Dr. C.J. Lobb
Dr. A.M. Malvezzi
Dr. E. Mazur
Dr. T.W. Mossberg
Dr. I. Nikolic
Dr. B.M. Ocko
Dr. W. Paul
Dr. P.S. Pershan
Dr. R. Suri
Dr. T. Taylor
Dr. M. Tinkham
Dr. D. von der Linde
Dr. R.M. Westervelt
Dr. K. Wohn
Dr. T.T. Wu
Dr. Y.H. Zou

INTRODUCTION

This report covers progress made in the period 1 April, 1984 to 31 March, 1985 for the eleven research units funded under the Joint Services Electronics Program at Harvard University. It is broken down into four major divisions of electronic research--solid state electronics, quantum electronics, information electronics control and optimization, and electromagnetic phenomena. It also includes a report of Significant Accomplishments which contains noteworthy results. These are: X-Ray Reflectivity Measurement of the Structure of the Surface of Water by Research Unit 3, Observation of Chaos in Josephseon Junctions Driven at Far-Infrared Frequencies by Research Unit 4, and The Application of Electromagnetic Surface Waves to Geophysical Prospecting from the Surface of the Earth by Research Unit 11. This significant accomplishment report is not duplicated in other sections of the Annual Report where other activities funded under the same research unit are described.

CONTENTS

I. SOLID STATE ELECTRONICS

Personnel

Prof. H. Ehrenreich
Prof. W. Paul
Prof. P.S. Pershan
Prof. M. Tinkham
Asst. Prof. C.J. Lobb
Assoc. Prof. R.M. Westervelt
Dr. H. Akoh
Dr. M. Deutsch
Dr. J.U. Free
Dr. K.C. Hass
Dr. O. Liengme
Dr. B.M. Ocko
Dr. S. Oguz
Mr. A. Braslav
Mr. J. Burnett
Mr. J. Crimmins
Mr. Q. Hu
Mr. M. Iansiti
Mr. S.M. Lee
Mr. R. Lempert
Mr. D. Schwartz

I.1 Electronic Structure of HgMnSe and Related Semiconducting Alloys.

H. Ehrenreich, K.C. Hass, and R. Lempert, Contract N00014-84-K-0465; Research Unit 1.

This group has been continuing work,[1,2] reported in previous proposals and annual reports, concerning the application of a semi-empirical tight-binding approach to the calculation of the electronic structure and other properties of 2-6 alloys. During the past year this effort has emphasized alloys containing Mn which have interesting magnetic properties of possible practical importance. The parameters required for implementation of the empirical tight-binding scheme are obtained from experimental data and local spin density ASW calculations performed in collaboration with A.E. Carlsson (University of Washington, St. Louis). These calculations pertain to a hypothetical tetrahedral antiferromagnetic MnTe and MnSe. The same type binding techniques are also being utilized within the coherent potential approximation for a calculation of the electronic structure of a pseudo-quarternary alloy consisting of Cd, Mn↑, Mn↓, and Te. The results will

permit examination of the effects of disorder on both the magnetic and electronic properties of the alloy. Correlation effects are included within the Hubbard model and treated within the Hartree-Fock approximation. The various approaches used here together with the variety of semiconducting dilute magnetic alloys being examined, should provide a reliable overview of the electronic structure of these materials.

References

1. K.C. Hass and H. Ehrenreich, "Empirical Tight Binding Description of $Hg_{1-x}Mn_xTe$ and $Hg_{1-x}Cd_xTe$," Proceedings of the MCT Workshop, *J. Vac. Sci. Technol.* A1, 1678 (1983).

2. K.C. Hass, B. Velický, and H. Ehrenreich, "Simplification of Green's Function Calculations Through Analytic Continuation," *Phys. Rev.* B29, 3697 (1984).

I.2 Magnetic Properties of Diluted Magnetic Semiconductors.

H. Ehrenreich, R. Lempert, and K.C. Hass, Contract N00014-84-K-0465; Research Unit 1.

Because of the unusual magnetic properties of dilute magnetic semiconductors, there has been a resurgence of interest in various fundamental aspects of the theory of their magnetism. These pertain to the exchange interaction between the Mn moments and conduction band electrons or valence band holes as well as the interaction among Mn moments themselves. The exchange associated with the electrical carriers is reponsible for the pronounced and possibly useful magneto-optical effects. That associated with the Mn-Mn interactions is important in the understanding of cluster antiferromagnetism and the spin-glass behavior that is observed at low temperatures. We are currently examining the hierarchy of Mn-Mn exchange mechanisms in 2-6 alloys such as those mentioned above using a generalized Anderson Hamiltonian and the electronic structure already described. The hybridization strength is extracted from experimental sp-d exchange constants using an analytic expression provided by the Schrieffer-Wolff transformation. All contributions to the Mn-Mn exchange for nearest and second nearest neighbors are calculated perturbatively to lowest non-vanishing order. Superexchange is found to dominate in agreement with the observed antiferromagnetic

coupling. Other contributions including the Bloembergen-Rowland mechanism and direct exchange are more than an order of magnitude smaller. The agreement between the calculated and experimental values of the nearest and next nearest neighbor exchange constants is very satisfactory. Similar calculations for other dilute magnetic semiconductors are in progress. They suggest that the dominance of superexchange is a general feature of this class of alloys. The chemical trends associated with changes in the non-magnetic constituents are also under examination by using these results and simplified, physically transparent perturbation expressions.[1]

Reference

1. Submitted to Solid State Com. (1985).

1.3 Semiconducting Pseudobinary Alloys. H. Ehrenreich, K.C. Hass, and R. Lempert, Contract N00014-84-K-0465; Research Unit 1.

The recent experimental discovery of a bimodal distribution of nearest neighbor bond lengths in (In, Ga)As and Zn(Se,Te) has raised new questions concerning the role of structural disorder in semiconducting alloys. During the past year we have presented the first self-consistent effective medium theory of the electronic structure of pseudobinary zincblende alloys and applied it to both alloy systems.[1] These calculations rely crucially on the molecular coherent potential approximation, which can be readily applied to pseudobinary alloys and includes the effects of both chemical and structural disorder. The results are surprising: besides showing that the effects of structural and chemical disorder are comparable in magnitude, there is evidence that both disorder effects, when considered together, can either enhance or diminish the total scattering of electrons in particular energy regions. The mobility of conduction band electrons is actually enhanced in the systems under consideration. The question of why these alloys, in view of the very appreciable associated lattice distortion should not form in the chalcopyrite structure remains open and is under investigation.[2]

References

1. K.C. Hass, R.J. Lempert, and H. Ehrenreich, "Effects of Chemical and Structural Disorder in Semiconducting Pseudobinary Alloys," *Phys. Rev. Lett.* 52, 77 (1984).

2. R. Lempert, K.C. Hass, and H. Ehrenreich, manuscript in preparation.

I.4 Dislocation-Free GaAs. H. Ehrenreich, Contract N00014-84-K-0465; Research Unit 1.

This research, performed in collaboration with J.P. Hirth (Ohio State University) examines the question of why the addition of a small amount of In to as-grown GaAs crystals should result in an appreciable reduction in dislocation density. The model proposed to explain this phenomenon is based on solid solution hardening, familiar in metallurgy. In the present case appreciable differences in the volume fraction to be associated with solute and solvent atoms respectively are likely to produce substantial reductions in dislocation density of the host crystal without deleterious effects on the electrical properties. This feature is likely to be relevant to alloy systems other than InGaAs. Furthermore, it may possibly provide some insight concerning the stability of strained superlattices. The results will appear shortly in *Applied Physics Letters*.[1]

Reference

1. H. Ehrenreich and J.P. Hirth, *Appl. Phys. Lett.*, to be published April 1, 1985 issue.

I.5 Charged Dislocations and Jogs in HgCdTe. H. Ehrenreich, Contract N00014-84-K-0465; Research Unit 1.

Jogs in dislocations in 2-6 compounds act as extrinsic sources for vacancies and interstitials. They carry effective charges and will therefore act as donors and acceptors. As a result they can influence the electrical properties of these compounds significantly. This research, performed in collaboration with J.P. Hirth (Ohio State University)[1] suggests reasons for the fact that HgCdTe alloys, which would ordinarily be p-type at low

dislocation densities converts to n-type after cleavage on a [110] plane or mechanical polishing. The insight provided is of considerable practical importance and probably of more general applicability.

Reference

1. J.P. Hirth and H. Ehrenreich, "Charged Dislocations and Jogs In $Hg_{1-x}Cd_xTe$ and Other II-IV Compounds," *J. Vac. Sci. Tech.*, to be published in March/April 1985 issue.

I.6 Optical Moment Sum Rules. H. Ehrenreich and K.C. Hass, Contract N00014-84-K-0465; Research Unit 1.

A methodology is introduced which utilizes relationships between moments of ε_2 in ordered and disordered systems as a test of the validity of electronic structure and chemical bonding models. The zeroth moment, related within a one-electron approximation to an average dipole matrix element, is particularly useful. We have made a detailed comparison of optical data for a variety of amorphous semiconductors and their corresponding crystals. Despite limited available data the present results strongly suggest that the difference between average dipole matrix elements associated with the amorphous and crystalline phase respectively is typically less than 15% for a given semiconductor. The difference is positive for tetrahedral semiconductors, zero for tetrahedral oxides, and negative for molecular semiconductors. These results have been used to discuss the validity of the "independent band model." Their significance has been explored by utilizing a real space picture which focuses on the effects of the short range environment. Some questions concerning the structure of amorphous semiconductors can be clarified with the help of analyses such as that developed through this research.[1]

Reference

1. K.C. Hass and H. Ehrenreich, "Electronic Structure Models, Bonding, and Optical Moments in Amorphous and Crystalline Semiconductors," *Annals of Physics*, to be published in October 1985 issue.

I.7 Photovoltaics. H. Ehrenreich, Contract N00014-84-K-0465; Research Unit 1.

During the period 1978-1980 the senior investigator was Chairman of a White House Panel on Photovoltaic Energy Sources which was sponsored by the American Physical Society. Since then he has served on a number of government and industrial panels that monitor the evolution of this technology. Most recent views are expressed in a paper in *Solar Cells*[1] and in testimony before the Subcommittee on Energy Development and Applications of the Committee of Science and Technology, House of Representatives, March 5, 1985.[2]

References

1. H. Ehrenreich, "Comments on Current Photovoltaic Technology," *Solar Cells* 12, 45 (1984).

2. Congressional Record, to be published.

I.8 Investigation of Amorphous Hydrogenated Si and Si-Ge Alloys. J-I. Hanna, P.B. Kirby, D. Leopold, K. Mackenzie, Z. Sun, J. Burnett, J. Eggert, Y-M Li, and W. Paul, Contracts N00014-84-K-0465, NSF DMR-81-08327 and SERI Subcontract XB-2-02144-1 of DOE Prime Contract DE-AC-02-83-CH10093; Research Unit 2 (former #3).

During this period we completed our investigation of the properties of amorphous hydrogenated alloys of Si and Ge made by glow discharge decomposition of appropriate mixtures of SiH_4 and GeH_4. These alloys have smaller forbidden energy gaps than a-Si:H, which potentially make them more suitable for most applications. In practice, they are usually found to have inferior photoelectronic properties, whose cause is still under investigation. The alloys investigated were made under conditions of different substrate temperature, r.f. power, and gas temperature and flow. After the usual chemical and structural characterization was done, measurements were made of electrical conductivity, optical absorption, photoconductivity and photoluminescence. These measurements were then correlated in order to give a self-consistent model of the electronic band structure and properties. A lengthy account of the systematic investigation of these alloys made from the decomposition of SiH_4-GeH_4 mixtures has been accepted for publication in the *Physical Review*.

During this period we have also undertaken to produce amorphous alloys of $Si_{1-x}Ge_x$ by the glow discharge decomposition of mixtures of SiF_4, GeF_4 and H_2. The idea of using F as a compensator atom for these alloys was suggested four years ago by the Principal Investigator, in order to improve the microstructure of the alloys by eliminating weak bonds. Subsequently a Japanese group discovered that material made in this fashion had superior photoconductive properties. We have carried out the same type of investigation for alloys made from these materials as from the hydrides, varying the gas pressures and flow rates and the applied r.f. power. The same battery of investigative property measurements was done. The result at the time of writing is that the photoconductive response is improved by an order of magnitude. Other properties have also changed to some extent. The interesting fundamental aspect of this work is that it appears likely that the disorder in the material may have been altered by the difference in compensation method. Thus there is a possibility that the extent of the band tails has been altered and that a different kind of diamagnetic defect state is prevalent in this material from that obtained in the alloys produced from the hydrides. The implications for the structure and properties of Si-Ge alloys, and other two-component alloys with compensated dangling bonds, are still under investigation.

I.9 Staebler-Wronski Investigation of a-Si:H, Doped a-Si:H, a-$Si_{1-x}Ge_x$:H Alloys and (P,B) Doped and Compensated a-Si:H. D.J. Leopold and W. Paul, Contracts NSF DMR-81-08327 and N00014-84-K-0465; Research Unit 2 (former #3).

The outstanding problem in the full utilization of a-Si:H and related amorphous materials for photoelectronic applications is the decrease in photoconductive response as a result of prolonged light irradiation. It is commonly believed that the cause is the production of a defect (dangling-bond) state in the recombination event which follows light irradiation. We have been investigating the production of such defects by measuring the changes in sub-band gap absorption and electrical transport caused by measured doses of radiation. The types of sample used have been a-Si:H, a-$Si_{1-x}Ge_x$:H and doped and compensated a-Si:H. The excitation spectral dependence of the changes in transport and optical absorption have been measured.

The particular thrust of our recent measurement has been the differences in properties between singly-doped a-Si:H and doped/compensated material. Using the constant photocurrent method to extend direct optical absorption measurements to sub-band gap energies, we have shown that doping a-Si:H either n-type with phosphorus or p-type with boron results in an increased defect density near midgap. Compensated a-Si:H samples show a large reduction in defect density compared with that in both singly-doped and undoped material. Also, the steady state photoconductivity is found to decrease when boron-doped material is compensated with phosphorus. This is consistent with time-of-flight measurements, which show a reduced drift mobility for electrons and holes in compensated material, implying the existence of new defect states in the band tails. The absorption spectra support the proposal that additional defect states are created in the band tails as increasing amounts of dopant are incorporated in compensated a-Si:H. The observed band tail broadening presumably reflects the presence of these additional defect states.

Light soaking experiments performed on doped a-Si:H samples show a dark conductivity decrease which is completely reversible upon annealing. Also, changes in photoconductivity recombination from a bimolecular to a monomolecular controlled process have been observed. Compensated material can give rise to either a dark conductivity decrease or increase after exposure to light, depending on the relative amounts of phosphorus and boron incorporated in the material. We have found activation energy shifts concomitant with these dark conductivity changes induced during light soaking. Presumably the Fermi level position moves in response to additional defect states created during exposure. Direct evidence for new defect states in the gap was inferred from a low energy absorption increase after optical exposure.

I.10 Metastable Semiconducting Alloys of $Ge_{1-x}Sn_x$. S. Lee, J. Burnett, and W. Paul, Contract N00014-84-K-0465; Research Unit 2 (former #3).

We have continued to make amorphous Ge-Si alloys by r.f. sputtering in an Ar plasma of a polycrystalline Ge target to which pieces of polycrystalline β-Sn are attached. The composition of the resulting films is determined by an electron microprobe. Crystallization is accomplished by melting with one 10 ns pulse from an excimer laser, in collaboration with personnel of Lincoln

Laboratory, and thereafter X-ray diffraction, Raman and electroreflectance studies are made. Since our last report, we have concentrated on understanding and separating out artifacts in the electroreflectivity experiment, caused by possible interferences due to the polyimide insulating film, from true critical-point electroreflectivity features in the crystallized Ge-Sn alloy.

That there was indeed the possibility of interference effects in the electroreflectivity spectrum was verified by measuring the electrically-unmodulated reflectivity spectrum of crystalline Ge on which the usual thickness of polyimide had been deposited. Maxima and minima in the reflectivity were found at the same energies as in the electroreflectivity spectrum, except for the well-established true critical-point features at 2.1 and 2.3 eV. Since the method of deposition of the polyimide film gives a very uniform film of about the same thickness in each run, it seemed reasonable that at least some of the maxima and minima in the electroreflectivity spectra of c-Ge, c-Si, and c-$Ge_{1-x}Sn_x$ were related to interferences in the polyimide. The photon energies of the observed maxima and minima were consistent with the optical thickness of the polyimide film. However, since the electroreflectivity spectrum measured only the change in the reflectivity when an electric field is applied, it is necessary that the field change the optical constants of the semiconductor-polyimide package. It is presumed that the most likely cause of this is a change in the refractive index of the semiconductor, but since a study of this is not the main objective of our investigation, we have tried instead to avoid the phenomenon. It should be remarked in passing, however, that these interference effects in the electroreflectivity spectrum are not observed for the amorphous $Ge_{1-x}Sn_x$ layers, while they appear for the crystallized $Ge_{1-x}Sn_x$. This would appear to indicate a difference in the effects of an electric field on the refractive indices of these amorphous and crystallized semiconductors.

In principle, these interference effects may be eliminated by roughening the crystal film surface before depositing the polyimide. A comparison was made of the electroreflectivity spectra of two codeposited Ge films, one of which had been etched with CP4 or $H_2O_2(1):HF(2):H_2O(30)$ before deposition of the polyimide layer. This film showed augmented electroreflectivity features at the energies of the E_1 (2.1 eV) and $E_1+\Delta_1$ (2.3) transitions, and no other oscillations. When a film of crystallized $Ge_{0.7}Sn_{0.3}$ was etched, all of the features observed in the electroreflectivity spectrum of an unetched film

between 1.1 and 2.3 eV disappeared below the noise level. Measurements over a more extensive photon energy range are now planned.

We have also made preliminary measurements of the Raman spectrum of amorphous and crystalline $Ge_{1-x}Sn_x$ for several values of x. For $x = 0$, pure Ge, the zone-center phonon energy was 300.2 cm^{-1} with an FWHM of 3.7 cm^{-1}, in agreement with values in the literature. For $x = 1$, pure α-Sn, maintained at low temperature by circulating liquid nitrogen, the zone-center phonon energy was 190.8 cm^{-1} with an FWHM of 4.7 cm^{-1}. These values agree to within 3 percent with those in the literature. To check further that we had not converted the α-Sn sample into β-Sn with the laser energy, we measured a sample of metallic β-Sn and determined that there were no Raman features at the same energy as the zone-center phonon of α-Sn. We also measured the Raman spectrum of amorphous Ge and found a shift and broadening in full agreement with the spectra in the literature. It thus appears that we are reasonably positioned to extend our measurements of the Raman spectra of laser-crystallized samples of $Ge_{1-x}Sn_x$ alloys of different x.

I.11 Light Scattering from Thin Smectic Films. S. Amador, Contracts N00014-84-K-0465 and NSF DMR-82-12189; Research Unit 3 (former #4).

The laser light scattering system has been made operational. The interfacing of the IBM-XT personal computer to the Langley Ford 1096 digital correlator and the appropriate stepping motors is now completed and preliminary data indicates the system is functioning according to design. Current efforts are directed towards stabilizing the temperature control system and preliminary characterization of samples.

I.12 X-Ray Scattering from Liquid, Liquid Crystal and Solid Surfaces. A. Braslau, J. Crimmins, D. Schwartz, B. Ocko, I. Tidswell, A. Weiss, M. Deutsch, and P.S. Pershan, Contracts N00014-84-K-0465 and NSF INT-83-11841.

The most important achievement in the present report period was the construction of a surface spectrometer that allows x-ray reflectivity studies of liquid surfaces using the Harvard Rotating Anode x-Ray Facility. Previously all such measurements were carried out at the synchrotron facility DESY

(HASYLAB) in Hamburg, Germany. The most important technical development that went into this spectrometer was a channel cut crystal monochromator, Ge(111), in which the beam is selected by two Bragg reflections. The monochromator is oriented such that the *first reflection* bends the beam downward by the Bragg angle (2θ) of 27.2 degrees. The second reflection bends the beam upward by an identical angle such that the emitted monochromatic beam is parallel to the incident beam. The monochromator and associated slits are mounted on a rigid bar whose position and orientation are computer controlled. In this way a single well-defined downward incident angle is selected from the output of the rotating anode x-ray source. The sample is on a computer controlled elevator that is continually adjusted so that the monocnromatic beam strikes the center of the sample. The reflected beam is detected by a scintillation detector-slit combination. Using this spectrometer it was possible to make preliminary measurements on the x-ray reflectivity from the surface of water. These measurements were then continued at the synchrotron facility in July of 1984.

The most important accomplishment of the preliminary measurements was the development of sample geometries that were not plagued by acoustically excited capillary waves. These results were published in the *Physical Review Lett.* (Braslau et al., *Phys. Rev. Lett.* 54, 114 (1985). Since those measurements we have been continuing to explore other liquid surface and have made extensive measurements on CCl_4 at HASYLAB, and methanol at Harvard. In addition, we have a further measurement on the following liquid crystals: 9CB, $\bar{8}$S5 at (HASYLAB); 8CB and DB7 (at Harvard), and one microemulsion system, AOT-oil-water as provided by John Huang of Exxon. The DB7 sample was provided by Cyrus Safinya of Exxon, and he participated in the measurement at Harvard. X-ray reflectivity measurements of selected solid substrates were also initiated using samples obtained from the Harvard Observatory. These samples are important since they are protypical of surfaces used in x-ray mirrors. We have seen both angular dependence of the reflectivity and diffuse, non-specular reflectivity. We are in the process of analyzing this data in order to determine and characterize the roughness of solid surfaces. One theoretical model has successfully explained most of the observed features; however there are discrepancies that indicate the model is not complete. X-ray studies of freely suspended thin films, and of the Nematic-Smectic-A phase transition have continued, however in the past year that work was primarily supported by other grants and will not be discussed further in this report.

I.13 Bi Barriers and SNS Proximity Effect Josephson Devices. O. Liengme and M. Tinkham, Contracts N00014-84-K-0465 and N00014-83-K-0383; Research Unit 4 (former #2).

Compared to tunnel junctions, metallic weak links present negligible shunting capacitance, but with ordinary metals, they usually have low resistances, which make impedance matching difficult in addition to causing severe heating problems at high voltages and frequencies. It has been proposed that a *semimetal* barrier might combine some of the advantages of metallic and tunnel barrier devices. In experiments now in progress, we find that Bi in the dirty limit is well described by the standard Ginzburg-Landau theories used for ordinary metal SNS junctions. This holds not only for the static properties, such as the temperature dependence of the critical current, but also for the numerical form of the finite voltage I-V curves, as computed with the TDGL theory. However, these experiments also show that the low Fermi velocity characteristic of a semimetal with low carrier density leads to a short coherence length unless the semimetal is very clean, so that the Josephson coupling is usually weak for links of substantial length. For realistic finite lengths, many questions remain open. For example, in our simulations and experiments to date we observe a cutoff frequency $\sim 2eI_cR/h$. Whereas this result is relatively well documented in the case of short devices, further work, both experimental and analytical, is underway to complete our understanding of this phenomenon in more general configurations where I_cR falls well below the short bridge limiting value.

II. QUANTUM ELECTRONICS

Personnel

Prof. N. Bloembergen
Asst. Prof. E. Mazur
Asst. Prof. T.W. Mossberg
Dr. N.W. Carlson
Dr. C.D. Cordero-Montalvo
Dr. H. Kurz
Dr. A.M. Malvezzi
Dr. D. von der Linde
Dr. Y.H. Zou
Mr. W.R. Babbitt
Mr. Y.S. Bai
Mr. J. Golub
Mr. J. Wang
Mr. A. Yodh

II.1 *Laser Pulse Shape Storage and Reproduction.* N.W. Carlson, W.R. Babbitt, Y.S. Bai, and T.W. Mossberg, Contracts N00014-84-K-0465 and DAAG-29-83-K0040; Research Unit 6 (former #5).

We have completed a series of experiments[1-3] which demonstrates that inhomogeneously broadened absorbers can "remember" the temporal shape of laser pulses used to resonantly irradiate them. We have also shown that the absorbers can be stimulated to emit a coherent light pulse whose shape duplicates the shape of an earlier excitation pulse (or its time reverse). Sample-generated signals have been observed to be up to 5 percent as intense as the original laser pulses. If one considers a pulse to consist of a digital data stream, it becomes obvious that the absorber's ability to remember to pulse's shape may be important in optical data storage applications.

In our first experiment[1] (which is basically a two-excitation-pulse photon echo experiment) we found that the photon echo signal constituted a time-reversed duplicate of the first laser excitation pulse (pulse 1). We performed a detailed study of the conditions necessary to ensure pulseshape reproduction. We found that all absorbing atoms within the bandwidth of pulse 1, must experience pulse areas less than or approximately equal to $\pi/3$. Excellent shape reproduction was found when the total duration of the second excitation pulse (pulse 2) was less than the temporal modulation time of pulse 1. In this case, the spectral components of pulse 2 are flat over the bandwidth of pulse 1. Surprisingly, we found excellent shape reproduction when pulse 2 is long provided that it is

intense. It turns out that shape correlation in this case results from a new type of power broadening in which absorbers at various frequencies respond identically in terms of both amplitude and phase to a strong laser field.

Photon echo pulseshape storage is mediated by an optical polarization which unfortunately means that it cannot persist for long periods. In our second experiment,[2] however, we have demonstrated that laser pulseshapes can be stored in the spectral distribution of population associated with a single quantum state. Populations may be extremely stable making this type of pulse-shape storage useful in optical memory application. Storage of pulseshape information in populations results from the interference between two laser pulses separated in time. The pulseshape information is recalled later by a third laser pulse which stimulates the sample to emit a duplicate or a time-reversed duplicate of one of the first two laser pulses. This processes can be viewed as a generalization of the stimulated photon echo. Our recalled signals were up to one percent as intense as the input pulses.

Finally, we demonstrated that laser pulseshapes can be stored in Zeeman coherences. The storage process is similar to that described in the previous paragraph, but the first two pulses are made to excite closely spaced adjacent transitions. As a result, pulseshape information is stored in stable coherences between nearly spaced energy levels.

Additional experiments are underway to elucidate the basic mechanisms associated with the above processes, and to demonstrate that they will be important in electro-optical technology.

References

1. N.W. Carlson, W.R. Babbit, Y.S. Bai, and T.W. Mossberg, "Field-inhibited Optical Dephasing and Shape Locking of Photon Echoes," *Opt. Lett.* 9, 232 (1984).

2. N.W. Carlson, Y.S. Bai, W.R. Babbitt, and T.W. Mossberg, "Temporally Programmed Free-induction Decay," *Phys. Rev.* A30, 1572 (1984).

3. N.W. Carlson, W.R. Babbitt, Y.S. Bai, and T.W. Mossberg, "Spectrally Ordered Zeeman Coherences and Optical Pulseshape Storage," accepted for publication in *J. Opt. Soc. Amer.* B.

II.2 Real-Time Optical Waveform Convolver/Cross-Correlator. Y.S. Bai, W.R. Babbitt, N.W. Carlson, and T.W. Mossberg, Contracts N00014-84-K-0465 and DAAG29-83-K0040; Research Unit 6 (former #5).

We have performed an experiment[1] demonstrating that optical coherent transient effects can be employed to perform convolutions and cross-correlations between the temporal waveforms of optical pulses. Assume that a series of three optical pulses resonantly excite an inhomogeneously broadened absorber. If one of the pulses is made temporally short while the other two are temporally structured, the sample is observed to emit a subsequent pulse possessing a temporal envelope proportional to the square of the convolution/cross-correlation of the electric fields of the temporally structured input pulses. The choice between convolution and cross-correlation is determined by which of the three input pulses is made temporally short. Optimized output signals were about one percent as intense as the input signals. In addition to our experiments, we performed numerical simulations to determine the input-pulse intensity regimes in which accurate convolutions/cross-correlations were obtained. It turns out that accurate convolutions/cross-correlations are obtained only when atoms in the absorber respond linearly to the input fields. This basic process may have important applications in optical computing systems.

Reference

1. Y.S. Bai, W.R. Babbitt, N.W. Carlson, and T.W. Mossberg, "Real-time Optical Waveform Convolver/Cross-correlator," *Appl. Phys. Lett.* 45, 714 (1984).

II.3 Optically Inhibited Collisional Dephasing. A.G. Yodh, J.E. Golub, N.W. Carlson, and T.W. Mossberg, Contracts N00014-84-K-0465 and NSF PHY-82-0780; Research Unit 6 (former #5).

We have studied[1] the effect of a strong laser field on gas-phase collisional relaxation. We find that a strong laser field acts to inhibit the collisional dephasing associated with the velocity-changing aspect of collisions. The laser field does not stop collisions, but it does stop some of the phase randomization normally introduced by them. Our experiment constitutes the first demonstration that gas-phase elastic collisional relaxation rates can be laser-field dependent. Knowledge that the collisional dephasing rates are laser-field dependent may be important in the modelling of gas laser dynamics.

Reference

1. A.G. Yodh, J. Golub, N.W. Carlson, and T.W. Mossberg, "Optically inhibited collisional dephasing," *Phys. Rev. Lett.* 53, 659 (1984).

II.4 Optical Pulse Compression Using Photon Echoes. Y.S. Bai and T.W. Mossberg, Contracts N00014-84-K-0465 and DAAG29-83-K0040; Research Unit 6 (former #5).

We have performed[1] a theoretical analysis of the photon echoes which may be generated with frequency-chirped optical pulses. We find that two linearly chirped excitation pulses produce echoes whose duration is roughly equal to the inverse chirp bandwidth. In calculating this result, we assumed that both excitation pulses have the same total bandwidth, but that the chirp rate of the second pulse is twice as large as that for the first pulse. The compressed pulse can be expected to contain on the order of ten percent as much energy as was contained in the first input pulse. The echo method may provide a very useful means of compressing long (i.e., microsecond) optical pulses.

Reference

1. Y.S. Bai and T.W. Mossberg, "Photon Echo Optical Pulse Compression," *Appl. Phys. Lett.* 45, 1269 (1984).

II.5 Nonlinear Four-Wave Mixing in Vapors. N. Bloembergen and Y.H. Zou, Contract N00014-84-K-0465; Research Unit 7 (former #6 and part of #5).

During the past year two comprehensive papers, on collision induced coherence and on collision induced population gratings respectively, have been published.[1,2] These give a detailed account of the experimental results of four wave light mixing in Na vapor with various buffer gases. The frequency of light beams is detuned by about 1 cm^{-1} from the $D_{1,2}$ resonance lines, so that collision induced effects are clearly dominant.

During the past year, a new phenomenon, the collision induced Hanle effect, has been observed and studied in some detail. This effect is a variation of the collision induced Zeeman coherences described in reference 1. A simple four-wave mixing configuration is used, as in conventional phase-conjugate reflection. All light beams have the same frequency and are derived

from a single dye laser. A standing wave pattern is produced by two light beams, polarized in the vertical direction. A third light beam makes a small angle (about 0.3°) with the first two and is polarized in the horizontal direction. The beams intersect in a cell, containing Na vapor and buffer gas, placed in a set of Helmholtz coils. The intensity of the phase-conjugate signal polarized horizontally and propagating in the backboard direction of the third beam, is plotted as the vertical component of the magnetic field is varied through zero. Hanle-type resonance with a FWHM width of about 30 milli-gauss have been obtained. The peak intensity of these resonances varies as the square or the cube of the buffer gas pressure. These first results on the collision induced Hanle effect have very recently been published.[3] A systematic study of these resonances is underway. Their parametric dependence on the nature and the pressure of the buffer gas, the detuning from the D_1 resonance line, the power level and polarization in the three incident laser beams, the admixture of other alkali-atoms, will be investigated further.

References

1. L.J. Rothberg and N. Bloembergen, "High-resolution Four-wave Light Mixing Studies of Collision-induced Coherence in Na Vapor," *Phys. Rev.* A30, 820 (1984).

2. L.J. Rothberg and N. Bloembergen, "High-resolution Studies of Collision-induced Population Grating Resonances in Optical Four-wave Mixing in Na Vapor," *Phys. Rev.* A30, 2327 (1984).

3. N. Bloembergen, Y.R. Zou, and L.J. Rothberg, "Collision-induced Hanle Resonances of Kilohertz Width in Phase-Conjugate Four-Wave Light Mixing," *Phys. Rev. Lett.* 54, 186 (1985).

II.6 Two-Photon Absorption Spectroscopy of Rare Earth Ions. C.D. Cordero-Montalvo, R.S. Rana, and N. Bloembergen, Contract N00014-84-K-0465; Research Unit 7 (former #6 and part of #5).

During the past year the $^1S_0$ level of the $4f^2$ configuration of Pr^{3+} in $LaCl_3$ has been found for the first time.[1] This forbidden two-photon transition $^3H_4 \rightarrow {}^1S_0$, with $\Delta J = 4$, $\Delta L = 5$ and $\Delta S = 1$, has also been studied[2] for the same ion Pr^{3+} in the host crystal LaF_3. Furthermore a two-photon absorption study of both cubic non non-cubic sites of the Gd^{3+} in CaF_2 has

been completed.[3] An invited review paper on two-photon spectroscopy of rare earth ion was presented at the International Conference on Luminescence, held in Madison, Wisconsin, in August 1984. With these publications the activities in this particular research topic have been terminated.

References

1. R.S. Rana, C.D. Cordero-Montalvo, and N. Bloembergen, "The $^1S_0$ level of Pr^{3+} in $LaCl_3$," *J. Chem. Phys.* 81, 2951 (1984).

2. C.D. Cordero-Montalvo and N. Bloembergen, "Two-Photon Transition from $^3H_4$ to $^1S_0$ in Pr^{3+} in LaF_2," *Phys. Rev.* B30, 438 (1984).

3. C.D. Cordero-Montalvo, "Two-Photon Absorption Spectroscopy of Multisite Gd^{3+} in CaF_2," *Phys. Rev.* B, accepted for publication, 1985.

4. N. Bloembergen, "The Solved Puzzle of Two-Photon Rare Earth Spectra in Solids," to be published in the Proceedings of the 1984 International Conference on Luminescence, *Journal of Luminescence*, North-Holland, Amsterdam, 31-32, 23 (1984).

II.7 Picosecond Laser Interactions with Semiconductors. H. Kurz, A.M. Malvezzi, D. von der Linde, G.-Z. Wang, and N. Bloembergen, Contracts N00014-84-K-0465 and N00014-83-K-0030; Research Unit 7 (former #6 and #5).

The extensive data on the carrier plasma density and lattice temperature during and following picosecond irradiation of silicon samples has been reviewed and analyzed theoretically in an invited paper[1] at the meeting of the Materials Research Society, held in Boston in November 1984. A theoretical investigation of the variation of the effective mass of the carriers at very high densities (10^{21}/cc) and temperatures up to the melting point has also been carried out.[2]

Experiments on the heating of a GaAs crystal under picosecond irradiation at 530 nm wavelength have used the method of reflected second harmonic generation. When the surface melts, the production of second harmonic radiation is suddenly reduced. This effect has been observed and reported.[3] It was concluded that the dense hot carriers exchange energy with the lattice with a characteristic time of less than 2 ps.

Current experiments focus on the evaporation of neutral particles from the superheated fluid. It has been established that the silicon surface readily reaches a temperature over 5000°K at a fluence of 0.5 J/cm^2 at 530 nm

wavelength. Thin film SOS samples are blown off. This blow-off phenomenon has hampered the study of the rate of evaporation. Experiments are now planned on metal films of aluminum, and possibly silver and gold. The lower melting points will hopefully permit the observation of a range of superheating without blow-off. A study of the heating and evaporation of silicon surfaces coated with SiO_2 layers has been published.[4]

A theoretical study was also made to obtain shorter pulses (2-3 ps instead of 20 ps) from a Nd-Yag mode-locked laser system by combining intracavity self-phase-modulation with external modulation.[5]

References

1. H. Kurz and N. Bloembergen, "Picosecond Photon-Solid Interaction," Proceedings of the Materials Research Society 1984 Symposium on Energy Beam-Solid Interactions and Transient Thermal Processing, edited by D.K. Biegelson, G.A. Rozgonyi and C.B. Shank, North-Holland, Amsterdam, 1985.

2. Guo-zhen Yang and N. Bloembergen, "Effective Mass of High-Density Carriers in Silicon," *Appl. Phys.* A, Springer-Heidelberg, submitted for publication.

3. A.M. Malvezzi, J.M. Liu, and N. Bloembergen, "Second Harmonic Generation in Reflection from Crystalline GaAs under Intense Picosecond Laser Irradiation," *Appl. Phys. Lett.* 45, 1019 (1984).

4. J.M. Liu, L.A. Lompré, H. Kurz, and N. Bloembergen, "Phenomenology of Picosecond Heating and Evaporation of Silicon Surfaces Coated with SiO_2 Layers," *Appl. Phys.* A, Springer-Heidelberg, 25 (1984).

5. D. von der Linde and A.M. Malvezzi, "Intracavity Self-Phase Modulation and Pulse Compression in Mode-Locked Lasers," *Appl. Phys.* A, Springer-Heidelberg, to be published, 1985.

II.8 Picosecond Laser-Induced Emission from Metals and Semiconductors.

H. Kurz, A.M. Malvezzi, and N. Bloembergen, Contracts N00014-84-K-0465 and N00014-83-K-0030; Research Unit 7 (former #6 and #5).

Careful experimental measurements of the photo-electric emission induced by $\lambda = 265$ nm picosecond pulses from a crystalline silicon surface have been completed over a wide range of incident fluences. At least three distinct regimes are observed. At fluences below about 0.02 J/cm^2, the emitted charge per pulse has a linear and quadratic component. The latter is due to

photo-emission from the dense hot carrier plasma. The origin of this nonlinear effect was confirmed by observation with temporally separated pulses. The synergetic effects, when the two pulses overlap in time, are consistent with this interpretation. In the second regime, with fluences in the range 0.02-0.15 J/cm^2 the photo-emission is space charge limited. This is in agreement with a theoretical analysis. At fluences above 0.15 J/cm^2, the photo-emitted electron charge increases very rapidly. At the same time, a strong emission of positive ions is detected. In this third regime, the evaporation during the picosecond pulse is sufficient to create the formation of a plasma. The space charge effects are neutralized by positive ions. The velocity of these positive ions has also been observed by a time-of-flight measurement. There is an indication of a fourth regime, in which ponderomotive nonlinear effects in the created plasma appear to become dominant.

These investigations have been presented[1] at the Materials Research Symposium in Boston, November 1984. A detailed account has also been accepted for publication elsewhere.[2]

We have also collaborated with the group of Professor Ippen at MIT to study the photo-emission by 75 femtosecond pulses. This work was supported by the Joint Services Electronics Program at MIT, and has been reported in a recent publication.[3]

With these reports the project on picosecond photo-emission has been terminated.

References

1. A.M. Malvezzi, H. Kurz, and N. Bloembergen, "Picosecond Photoemission Studies of the Laser Induced Phase Transition in Silicon," Proceedings of the Materials Research Society 1984 Symposium on Energy Beam-Solid Interactions and Transient Thermal Processing, edited by D.K. Biegelsen, G.A. Rozgonyi and C.V. Shank, North Holland, Amsterdam, 1985.

2. A.M. Malvezzi, H. Kurz, and N. Bloembergen, "Nonlinear Photoemission from Picosecond Irradiated Silicon," *Appl. Phys.* A, Springer-Heidelberg, accepted for publication, 1985.

3. J.G. Fujimoto, J.M. Liu, E.P. Ippen, and N. Bloembergen, "Femtosecond Laser Interaction with Metallic Tungsten and Nonequilibrium Electron and Lattice Temperatures," *Phys. Rev. Lett.* 53, 1837 (1984).

II.9 Multiphoton Vibrational Excitation of Molecules. E. Mazur, J. Wang, and N. Bloembergen, Contract N00014-84-K-0465; Research Unit 8 (former #7).

Time-resolved Raman spectroscopy of infrared multiphoton excited molecules has proven to be a powerful tool in the study of intramolecular dynamics. In particular, information on the intramolecular energy distribution can be obtained as a function of time and infrared laser fluence.

During this reporting period substantial modifications and improvements were made to the equipment in our laboratory. First, the high-power picosecond CO_2 laser has been overhauled. This was necessary, since the proposed measurements require hundreds of thousands of lasershots, and the present set-up had been operating approximately five years without any modification. Second, in order to substantially reduce the consumption of gas, a gas-recirculation system is being added to the CO_2 laser facility. Finally, the old computer system, which had an inadequate level of performance, has been replaced by a totally new computer-controlled data-acquisition system, consisting of a Digital computer and a CAMAC crate. These changes constitute major improvements which will make better and more efficient measurements possible.

We plan to continue the experimental study of intramolecular energy transfer between infrared and Raman active modes. Measurements will be performed in systems where several Raman active modes can be observed, in order to determine if the excitation of these modes (after infrared multiphoton excitation, but before any collisions take place) corresponds to a common temperature.

During the past year several publications have either appeared,[1-3] or are in the course of publication,[4] which review the systematic trends of multiphoton infrared vibrational excitation as a function of molecular size and the vibrational density of states. These papers are based on the large body of systematic experimental work carried out under this project over the past five years.

References

1. N. Bloembergen, I. Burak, and T.B. Simpson, "Infrared Multiphoton Excitation of Small Molecules," *J. Molecular Structure* 113, 69-82 (1984).

2. N. Bloembergen, I. Burak, E. Mazur, and T.B. Simpson, "Infrared Multiphoton Excitation of Small Molecules," *Israel J. Chem.* 24, 179 (1984).

3. Nicolaas Bloembergen and Ahmed H. Zewail, "Energy Redistribution in Isolated Molecules and the Question of Mode-Selective Laser Chemistry Revisited -- New Experiments on the Dynamics of Collisionless Energy Redistribution in Molecules Indicate Possibilities for Laser-Selective Chemistry with Subpicosecond Pulses," *J. Phys. Chem.*, 88, 5459 (1984).

4. T.B. Simpson, J.G. Black, I. Burak, E. Yablonovitch, and N. Bloembergen, "Infrared Multiphoton Excitation of Polyatomic Molecules," submitted for publication to *J. Chem. Phys.* (1985).

III. INFORMATION ELECTRONICS CONTROL AND OPTIMIZATION

Personnel

Prof. R.W. Brockett
Assoc. Prof. C.I. Byrnes
Prof. Y.C. Ho
Asst. Prof. R. Suri
Dr. J. Baillieul
Dr. B. Bonnard
Dr. X. Cao
Dr. I. Nikolic
Dr. T. Taylor
Dr. K. Wohn
Mr. A. Bloch
Mr. W. Cebuhar
Mr. G. Diehl
Mr. J. Dille
Ms. V. Haimo
Mr. W. Jian
Mr. J. Loncarić
Mr. A. McIvor
Mr. D. Montana
Mr. S. Peck
Ms. B. Sanders
Mr. M. Zazanis

III.1 Conditional Density Approach to Tracking. R.W. Brockett, A. McIvor, and K. Wohn, Contracts N00014-84-K-0465 and N00014-84-K-0504; Research Unit 9 (former #8).

Given noisy versions of successive pictures of a scene which contains a moving object, it is natural to attempt to compute the conditional probability of the motion parameters. These parameters, e.g. the translational and rotational velocities, the position and orientation, etc., may realistically be assumed to satisfy stochastic differential equations. The observations which the motion generates can be thought of as the gray levels associated with the individual pixels of the camera which tracks the motions. The signals which underlie these observations are highly correlated and the noise tends to be correlated as well. Experiments show that very significant errors result if these correlations are ignored. As might be expected, the differences between gray levels of neighboring pixels gives a random process with much less spatial correlation. In fact, we observe that it is often possible to get satisfactory results by modeling these differences as being independent random variables. The resulting conditional density equation has been derived and propagated in some simple situations. This probabilistic

model seems to work well and extensions to more complex problems are being pursued.

III.2 Probabilistic Methods in Single Frame Picture Processing. R.W. Brockett, A. McIvor, and W. Jian, Contracts N00014-84-K-0465 and N00014-84-K-0504; Research Unit 9 (former #8).

The work of Alan McIvor[1] is devoted to a two-dimensional innovations approach to picture processing. It is rather intuitive that if one has a jump process which switches between two Gauss Markov processes then a whitening filter followed by a demodulator would be a suitable "perfect" detector of the jump process. We have shown that various algorithms in use in picture processing can be interpreted as approximations to this.

We have also investigated probabilistic approaches to edge tracking. This involves constructing a probabilistic model for edges. In this area we have investigated two possibilities, one based on modeling the curvature as a Gauss Markov process and the other based on modeling it as a finite state process. Results of computer simulations indicate that while there is something to be gained from each approach, sharp corners cause problems. We have also investigated a two point boundary value problem type interpolation scheme to continue edges through faint regions. This work will be reported on in the forthcoming thesis.[1]

Reference

1. Alan McIvor, Probabilistic Models in Computer Visions, Ph.D. Thesis, Division of Applied Sciences, Harvard University, to appear.

III.3 Multimode-Nonlinear Control. R.W. Brockett, Contracts N00014-84-K-0465, DAAG29-79-C-0147, AFSOR-81-7401, ECS-81-21428; Research Unit 9 (former #8).

Recent work on nonlinear control has emphasized problems for which the nonlinear effects are analytic functions. On the other hand, static friction, one of the most frequently encountered nonlinear effects, is definitely not analytic. In a recent paper[1] we undertook a study of what we call "multimode" systems--a class which includes circuits with diodes and gear trains with

deadzone, backlash and friction. The main results in this paper give a measure of how much performance degradation such effects cause. In addition, we present a convenient formalism for describing such systems. The most tractable class of useful models seems to be that of piecewise linear systems with the added feature that in some "boundary regions" the order of the system drops. This reflects, for example, a diode shorting out a capacitor when its voltage goes positive or gears leaving a backlash region. This formalism suggests a convenient simulation description as well.

Reference

1. R.W. Brockett, "Smooth Multimode Control Systems," *Proceedings of the 1983 Berkeley/Ames Conf. on Nonlinear Problems in Control and Fluid Dynamics*, (L. Hunt and C. Martin, eds.), Math. Sci. Press, 103-110, 1984.

III.4 Discrete Event Dynamic Systems Study. Y.C. Ho, R. Suri, X. Cao, G. Diehl, B. Sanders, J. Dille, and M. Zazanis, Contract N00014-84-K-0465, N00014-79-C-0776, and NSF ECS-82-13680; Research Unit 10 (former #9).

We continue the study described last year at the triannual JSEP review on discrete event systems. Specifically:

In the area of perturbation analysis (P/A) of DEDS, we resolved certain open theoretical question concerning the interchange of differentiation and expectation operators for M/G/1 queueing systems. We also showed that P/A could be used for very fast optimization of M/G/1 queues.[2] We have also presented an analytical proof that P/A is much more efficient than alternative techniques for sensitivity analysis of a general class of systems.[3]

In the area of manufacturing systems, we have continued our efforts in the study of flexible manufacturing as well as providing system-theoretic approaches to manufacturing systems in general.[9]

In the communication network area, we completed a study[12] of decentralized flow control based on the concept of a market mechanism for the allocation of scarce resources. The basic idea is to make each user declare what he/she needs and to allocate optimally based on these declarations. The important things here is that the payment scheme for the resources is designed

to induce each user to report *truthfully* in his/her own interest. Furthermore, no central authority is needed to make such allocations. Local flow control decision based on delayed reporting of declaration from other sources can be used and proved to yield stable allocations over time.

References:

1. Y.C. Ho, R. Suri, X.R. Cao, G.W. Diehl, J.W. Dille, and M. Zazanis, "Optimization of Large Multiclass (non-product form) Queueing Networks Using Perturbation Analysis," *J. of Large Scale Systems*, Dec. 1984.

2. R. Suri and M. Zazanis, "Perturbation Analysis is Exact for the M/G/1 Queue," *Proc. 23rd IEEE Conf. Decision and Control*, Las Vegas, Dec. 1984.

3. M.Z. Zazanis and R. Suri, "Comparison of Perturbation Analysis with Conventional Sensitivity Estimates for Regenerative Stochastic Systems," January 1985, submitted to *Operations Research*.

4. K,E. Stecke and R. Suri, "Flexible Manufacturing Systems: Operations Research Models and Applications," *Proc. ORSA/TIMS FMS Conference*, August 1984.

5. R. Suri and Whitney, "Decision Support Requirements in Flexible Manufacturing," *Journal of Manufacturing Systems* 3, 1, 61-69 (May 1984).

6. R. Suri and R.R. Hildebrandt, "Modelling Flexible Manufacturing Systems Using Mean-Value Analysis," *Journal of Manufacturing Systems* 3, 1, 27-38 (May 1984).

7. R. Suri and J.W. Dille, "On-Line Optimization of Flexible Manufacturing Systems Using Perturbation Analysis," *Proc. ORSA/TIMS FMS Conference*, August 1984.

8. R. Suri, "An Overview of Evaluative Models for Flexible Manufacturing Systems," *Proc. of ORSA/TIMS FMS Conference*, August 1984.

9. R. Suri, S.B. Gershwin, R.R. Hildebrandt, and S.K. Mitter, "A Control Theorist's View on Recent Trend in Manufacturing Systems," *Proc. of 1984 Conf. on Decision and Control*, Las Vegas, Dec. 1984.

10. R. Suri, "Generalized Quick Bound for Performance Evaluation of Queueing Networks," *Computer Performance* 5, 2, 116-120 (June 1984).

11. R. Suri and T.C. Tay, "Error Bounds for Performance Prediction in Queueing Networks," submitted to *ACM Trans. on Computer Systems*, July 1984.

12. B. Sanders, "Decentralized Resource Allocation Algorithms with Application to the Flow Control of Communication Networks," Ph.D. Thesis, Jan. 1985.

13. Y.C. Ho and D. Teneketzis, "On the Interactions of Incentive and Information Structure," *IEEE Trans. on Automatic Control* AC-29, 7 (1984).

14. P. Luh, T.S. Chang, and T. Ning, "Three Level Stackelberg Decision Problems," *IEEE Trans. on Automatic Control* AC-29, 3 (1984).

15. T.S. Chang and P. Luh, "Derivation of Necessary and Sufficient Conditions for Single Stage Stackelberg Games via the Inducible Region Concept," *IEEE Trans. on Automatic Control* AC-__, 1 (1984).

16. R. Suri and G.W. Diehl, "A New 'Building Block' for Performance Evaluation of Queueing Networks with Finite Buffers," *ACM Performance Evaluation Review* 13, 134-142 (1984). (Also submitted to *Management Science*.)

17. Y.C. Ho, Articles on "Team Theory and Information Structure, Stochastic Games and the Problem of Information" for the *Encyclopedia of Systems and Control* (1986).

18. R. Suri, "Quantitative Techniques for Robotic Systems Analysis," *Handbook of Industrial Robotics*, S. Nof, ed., John Wiley, New York, 1985).

19. Y.C. Ho, Z.J. Yang, and L. Servi, "Incentive Compatible Allocation Algorighm for Non-separable Group Payoff," *Optimal Control: Applications and Methods* 5, 4 (Dec. 1984).

20. X. Cao and Y.C. Ho, "Perturbation Analysis of Sojourn Times in Queueing Networks," to appear in *Operations Research*, 1985.

21. P. Luh, Y.P. Zheng, and Y.C. Ho, "Credibility in Stackelberg Games," *System and Control Lett.* 5, 3 (1985).

22. C. Cassandras and Y.C. Ho, "An Event Domain Formalism for Sample Path Perturbation Analysis of Discrete Event Dynamic Systems," *IEEE Trans. on Automatic Control*, to appear (1985).

23. Y.C. Ho, "On the Perturbation Analysis of Discrete Event Dynamic Systems," *J. of Optimization Theory and Application*, to appear (1985).

24. X. Cao, "The Dependence of Sojourn Times on Service Times in Tandem Queues," *J. of Applied Probability* 21, 661-666 (Sept. 1984).

25. X. Cao, "Convergence of Parameter Sensitivity Estimates in a Stochastic Experiment," to appear in *IEEE Trans. on AC*, Sept. 1985.

26. X. Cao and Y.C. Ho, "Performance Sensitivity to Routing Changes in Queueing Networks and Flexible Manufacturing Systems Using Perturbation Analysis," *IEEE J. on Robotics and Automation*, to appear (1985).

27. X. Cao, "On the Sample Functions of Queueing Networks with Applications to Perturbation Analysis," submitted to *Operations Research*.

IV. ELECTROMAGNETIC PHENOMENA

Personnel

Prof. T.T. Wu
Prof. R.W.P. King
Dr. J.T. deBettencourt
Mr. J.M. Dunn (until 9/30/84)
Mr. M.F. Brown
Ms. M. Owens
Mr. W.-Y. Pan
Ms. B.H. Sandler

Research in the area of electromagnetic radiation is directed toward the solution of practical problems through the complete understanding of the underlying physical phenomena. This involves the coordinated application of modern analytical, numerical, and experimental techniques and the use of high-speed computers and precision instrumentation. Application is also made of modeling techniques and the principle of similitude. Most practically significant problems in the area are sufficiently complicated that extensive computation and measurement are often required to justify approximations that are usually necessary. Where possible, general formulas are obtained and verified experimentally so that the phenomenon under study can be understood physically in analytical form and not just as a set of numbers.

The researches are concerned primarily with the properties of antennas and arrays and of the electromagnetic fields they generate in various practically important environments that lead to difficult problems with complicated boundary conditions. Examples include dipoles, traveling-wave antennas and arrays, crossed dipoles, and loops near the boundary between two media such as air and earth or sea water, and rock and sea water; the scattering of electromagnetic waves from buried or submerged objects; the properties of lateral electromagnetic waves and pulses; the field inside and currents and charges induced on obstacles within an emp simulator; arrays of antennas along curves lines; and solitary electromagnetic pulses with slow decay.

IV.1 Theoretical Study of Scattering from Buried or Submerged Objects. R.W.P. King, T.T. Wu, and W.-Y. Pan, Contract N00014-K-0465; Research Unit 11 (former #10).

The detection and localization of buried or submerged objects or inhomogeneities in a dissipative half-space from measurements of a scattered electromagnetic field are of current interest. Earlier investigations have been concerned primarily with plane waves incident on the surface of the earth from the air above at an arbitrary angle. The present study deals with the incident fields generated by horizontal and vertical antennas located on the surface of the earth. The first step in the analysis is the determination of this incident field. The complete electromagnetic field parallel to the surface of salt water has been determined[1,2] when the source is a horizontal electric dipole either with open ends or grounded at its ends. The dipole is in the air at a small height d above the water. Actually such an antenna is equivalent to an eccentrically insulated antenna lying on the surface of the half-space. The effective thickness of the insulation is d. This type of antenna has the properties of a transmission line with a complex wave number and characteristic impedance. By determining the distribution of current and the effective length of the antenna, the entire field along the surface of the earth can be readily obtained with the help of newly derived comprehensive formulas. The components of primary interest are those tangent to the boundary surface, viz., $E_{1\rho}$ or $B_{1\phi}$ and $E_{1\phi}$ or $B_{1\rho}$. The field of the open-ended dipole is found to be simpler than that of the terminated dipole since the currents in the vertical terminations of the latter generate a significant field consisting of the three components E_ρ, E_z and B_ϕ. The combined field of the horizontal and vertical members of the complete antenna can be quite complicated if the height d, and with it the length d of the vertical elements, is sufficient to make the contributions from them comparable to that from the horizontal element. At close range E_ρ and E_ϕ are comparable in magnitude. At distances for which $k_2\rho > 1$, E_ρ is significantly greater since it decreases only as $1/\rho$ whereas E_ϕ decreases as $1/\rho^2$. The cylindrical components E_ρ and E_ϕ are individually simpler than the related Cartesian components E_x and E_y.

Once the incident field is known, the scattered field can be investigated. The first scattering object studied is the horizontal insulated conductor.[3] This provides a scattered field that is readily calculated and combined with the

incident field to obtain a total field that exhibits interference phenomena. The length of the insulated metal rod was chosen to be near resonance at the operating frequency for the range of submerged depth d considered. The incident lateral-wave field is maintained by a horizontal dipole a height d_t in air above the surface of the earth, as described above. The total field, i.e., the incident plus scattered fields, is observed in the air also just above the surface of the earth. The current induced in the insulated wire by the lateral-wave field incident from the transmitter is evaluated first and then the re-radiated field just above the surface is calculated. Two orientations are considered: The field at the center of the buried conductor is (1) parallel to $E_{1\rho}(\rho,0,z)$, and (2) parallel to $E_{1\phi}(\rho,\pi/2,z)$. The incident, scattered and total fields in an area above the conductor have been evaluated for the conditions of a laboratory model. It is clearly demonstrated that a significant change in the electric field over the volume occupied by the scattering object is observed and that this is sufficiently localized to permit an accurate bounding of the area above the object. The scattering from objects like a metal disk or any region with a wave number that is significantly different from that of the ambient medium will be investigated quantitatively since the method has definite promise for discovering and locating underground oil fields. Extensive measurements in a salt-water-filled tank[4] containing a submerged metal disk have demonstrated the feasibility of the method.

Only a few scattering problems involving very simply shaped targets can be solved analytically. In a separate study by W.-Y. Pan, analytical expressions have been obtained for the scattered field from a buried, perfectly conducting rectangular plate placed parallel to the interface between air and earth.[5] First, the current is expressed in terms of several Tchebichef polynomials of the second kind. The scattered field is the sum of the fields that are generated separately by equivalent horizontal dipoles and multipoles. The moments of the dipoles and multipoles are obtained from the coefficients of the current expansion. These coefficients have been calculated over a frequency range from 13 to 160 kHz and a range of plate sizes from 2 to 20,000 square meters in area.

References

1. R.W.P. King, "On the Scattering of Lateral Waves by Buried or Surbmerged Objects," presented at the National Radio Science Meeting, Boston, MA, June 1984.

2. R.W.P. King, "The Scattering of Lateral Waves by Buried or Submerged Objects, I. The Incident Lateral-Wave Field," *Journal of Applied Physics* (scheduled for 1 March 1985 issue).

3. R.W.P. King, "The Scattering of Lateral Waves by Buried or Submerged Objects, II. The Electric Field on the Surface Above a Buried Insulated Wire," *Journal of Applied Physics* (scheduled for 1 March 1985 issue).

4. R. Bansal, "Electromagnetic Scattering from Conducting Objects Immersed in a Dissipative Half-Space," presented at the National Radio Science Meeting, Boston, MA, June 1984.

5. W.-Y. Pan, "The Scattered Field from a Buried, Perfectly Conducting Plate in a Lossy Earth," *Electromagnetics* (submitted for publication).

IV.2 Numerical and Analytical Determination of the Fields of Antennas Near an Interface Between Two Half-Spaces with Significantly Different Wave Numbers.

T.T. Wu, R.W.P. King, B.H. Sandler, and W.-Y. Pan, Contracts N00014-84-K-0465 and N00014-79-C-0419; Research Unit 11 (former #10).

Because the recently derived sets of formulas for the complete electromagnetic fields of horizontal[1-3] and vertical[4] electric dipoles on or near the boundary between two half-spaces are both simple and accurate, they have provided new insight into lateral-wave propagation in general and more flexible tools for a variety of specific applications. Examples of their usefulness are presented in several new papers. One paper[5] describes a number of practical antennas potentially useful in communicating with submarines. These include bare vertical monopoles and arrays of such monopoles in air on the earth's surface; horizontal traveling-wave antennas (Beverage antennas) or arrays of such antennas in air close to the surface of the earth or the sea; and insulated traveling-wave elements in the sea used either singly or in arrays designed to provide a radially progressive field with a maximum vertically upward. The properties of the antennas are evaluated in the frequency range $10 \leqslant f \leqslant 30$ kHz which is optimum for depths up to 50 m.

A second paper[6] demonstrates even more clearly that the new formulas for the surface-wave fields of antennas near a boundary surface have provided an

expanded horizon for understanding and using surface waves. By examining the formulas, surface waves are seen to have unusual properties that make them valuable tools in geophysical prospecting. The formulas show that over all distances and at all frequencies a signal reaching a receiving dipole in the salt water near the sea floor has, in effect, proceeded downward from the transmitting dipole in the sea water into the rock, then radially outward in the rock, and finally upward and back into the sea water to the receiving dipole. The decrease in amplitude and change in phase with radial distance depend primarily on the electrical properties of the *rock*. With a suitable choice of frequencies and radial distances ρ between transmitting and receiving dipoles, the received signal can have the simple form $\exp(-\alpha\rho)\exp(i\beta\rho)/\rho$, where α is the attenuation constant and β is the real wave number of the rock. These important facts are the basis for the development of methods for the determination of the conductivity and permittivity of the rock forming the sea floor by means of measurements made in the adjacent sea water. Since lateral waves do not penetrate deeply into the ocean floor, they are useful primarily in determining the average conductivity and permittivity of the materail fairly close to the boundary. For this, a two-layer theory may be adequate. In this same paper[6] the new formulas are used to assist in the interpretation of available measurements of the conductivity of the sea floor. It appears that the measured data would be well satisfied by a half-space model of the lithosphere that is homogeneous but one-dimensionally anisotropic in the conductivity. Such a model involves no reflections from deeper, widely spaced horizontal layers. An analytical study by W.-Y. Pan of the one-dimensionally anisotropic half-space is now in progress. Preliminary results show that with $\sigma_z \neq \sigma_x = \sigma_y$, the components $E_{1\rho}$, E_{1z} and $B_{1\phi}$ of electric type depend primarily on σ_z, while the components $E_{1\phi}$, $B_{1\rho}$ and B_{1z} of magnetic type depend primarily on $\sigma_x = \sigma_y$. This behavior agrees with the available measured data. A paper on this subject is being prepared.

A summary paper which discusses these various applications of lateral electromagnetic waves has been presented at a recent scientific meeting[7] and submitted for a special issue of the IEEE Transactions on Antennas and Propagation.[8]

Currently the Wu-King formulas are being used to determine certain properties of lateral waves, such as the maximum depth of penetration into Region 2

of the lateral-wave part of the field, and the fraction of power associated with the lateral wave in a specified range. To accomplish this, it is necessary to obtain explicit formulas for the complete field in Region 2 and, from them, the locus of the Poynting vector. These have been derived, and a paper applying this information to the use of horizontal antennas on the sea floor for geophysical exploration of the lithosphere is being written.

References

1. T.T. Wu and R.W.P. King, "Lateral Waves: A New Formula and Interference Patterns," *Radio Science* 17, 521-531 (May-June 1982).

2. T.T. Wu and R.W.P. King, "Lateral Waves: New Formulas for $E_{1\phi}$ and E_{1z}," *Radio Science* 17, 532-538 (May-June 1982); Correction, vol. 19, 1422, (Sept.-Oct. 1984)

3. R.W.P. King and T.T. Wu, "Lateral Waves: Formulas for the Magnetic Field," *Journal of Applied Physics* 54, 507-514 (Feb. 1983); Erratum, vol. 56, 3365 (Dec. 1984).

4. R.W.P. King, "New Formulas for the Electromagnetic Field of a Vertical Electric Dipole in a Dielectric or Conducting Half-Space Near Its Horizontal Interface," *Journal of Applied Physics* 53, 8476-8482 (Dec. 1982); Erratum, vol. 56, 3366 (Dec. 1984).

5. R.W.P. King and M.F. Brown, "Lateral Electromagnetic Waves Along Plane Boundaries: A Summarizing Approach," *Proc. of the IEEE* 72, 595-611 (May 1984).

6. R.W.P. King, "Electromagnetic Surface Waves: New Formulas and Their Application to Determine the Electrical Properties of the Sea Bottom," *Journal of Applied Physics* (submitted for publication).

7. R.W.P. King, "Electromagnetic Surface Waves: New Formulas And Applications," presented at the 1984 International IEEE/AP-S Symposium, Boston, MA, June 1984.

8. R.W.P. King, "Electromagnetic Surface Waves: New Formulas and Applications," *IEEE Trans. on Antennas and Propagation* (Special Issue),(submitted for publication).

IV.3 Reflection and Scattering of Lateral Waves at Vertical Discontinuities.

R.W.P. King and M.F. Brown, Contracts N00014-84-K-0465 and N00014-79-C-0419; Research Unit 11 (former #10).

The propagation of electromagnetic waves along boundaries between quite different media is predominantly by lateral waves. This is well understood along smooth boundaries, but the scattering of lateral waves at boundaries and discontinuities is not well understood. A theoretical study has been made[1] of the effect on the field generated by a horizontal dipole due to vertical discontinuities on both sides of the boundary between earth (water) and air. The two types of reflecting boundaries considered are: a) vertical discontinuities in the denser medium (earth, water) in the form of changes in the wave number from k_1 to k_3: and b) vertical projections into the less dense medium (air) in the form of thin walls of the denser medium. The analysis shows that reflections from the discontinuities in the denser half-space are extremely small even when k_1 changes from a value characteristic of salt water to a value $(k_3 \to \infty)$ characteristic of a perfect conductor (metal). Reflections from metal walls in air when $k_3 \sim \infty$ are much larger but still quite small when the height of the wall is a tenth of a wavelength or less. They are very significant when the wall is a quarter-wavelength high. These results are readily understood if it is recalled that the vertical unit dipole in air is very superior to the vertical unit dipole in salt water as a generator of lateral waves. Standing-wave patterns due to incident and reflected lateral waves are determined and shown graphically.

The reflections of lateral waves at cylindrical discontinuities above and below the salt-water surface have been measured[2] in a semicircular tank at two frequencies, $f = 644$ MHz and $f = 1.5$ GHz. Simple combinations of horizontal and vertical metal planes were chosen as the discontinuities. The measurements confirm the theoretical predictions discussed above. The small reflections from the ceiling were also studied experimentally and theoretically in their effect on both traveling and standing lateral waves. The measured $E_{1\rho}$ field patterns involve, in general, three waves: 1) the direct lateral waves with both vertical and radial components traveling radially outward from the source; 2) reflections from the cylindrical boundary in the form of lateral waves traveling radially inward toward the source and producing a regular standing-wave pattern; and 3) transverse plane waves coming from the ceiling at normal

or near normal incidence and polarized with the electric field in the radial direction. These produce interference patterns with traveling and standing lateral waves that are quite different from ordinary standing waves produced by similar waves traveling in opposite directions. It appears that the complications introduced by the finite size and indoor location of the tank are now well understood.

In a separate but related study, the lateral-wave field is incident upon and scattered by a thin metal cylinder. The usefulness of the new analytical formula for the z-component of the electric field and the generalization of the theory to fatter cylinders are discussed in a recently presented paper.[3] The measurements of both incident and scattered fields for thin and fat cylinders near the interface between two regions of a model lithosphere, one or both of which may be described by complex wave numbers, are presented.

References

1. R.W.P. King, "On the Reflections of Lateral Electromagnetic Waves from Perpendicular Boundaries," *J. of Appl. Phys.* 55, 3916-3926 (June 1984).

2. M.F. Brown, R.W.P. King, and T.T. Wu, "Experiments on the Reflection of Lateral Electromagnetic Waves," *J. of Appl. Phys.* 55, 3927-3933 (June 1984).

3. M.F. Brown, "Scattering of a Lateral Electromagnetic Wave by a Metal Cylinder," presented at the National Radio Science Meeting, Boston, MA, June 1984.

IV.4 Lateral-Wave Propagation and Modeling of the Lithosphere. M.F. Brown, R.W.P. King, T.T. Wu, and J.T. deBettencourt, Contracts N00014-79-C-0419 and N00014-84-K-0465; Research Unit 11 (former #10).

The first of a series of experiments which will culminate in an experimental and theoretical treatment of lateral-wave pulses has been undertaken. The preliminary problem of determining the fundamental transient-response characteristics of dipole antennas in an indoor environment has been studied. In addressing this problem, two vertical monopoles have been used above a metal ground plane. A receiving monopole has been designed to function in a mode which eliminates noise by utilizing a twin-measurement procedure developed in conjunction with emp simulator measurements.[1] In such a procedure, the

received signal is measured twice, once with the monopole pointing "down" (at the ground plane) and once "up". The signals are processed by a waveform computer programmed to subtract the two signals at its input so that any induced currents in the laboratory which are not part of the transmitted pulse are eliminated.

The pulse waveforms of the received signal for various separations between the dipoles have been plotted together with the associated Fourier transforms. Plots of the electric field versus time have proved to be quite complicated, i.e., with multiple maxima and minima, for the first choice of transmitting-antenna length (13.5 cm). The Fourier transform of this field shows a maximum at $\sim$ 500 MHz, while the shortest wavelength component is $\sim$ .8 GHz. The origins of the complicated pulse sequence have been investigated by studying i) the resonance qualities of the dipole transmitting antenna, ii) the effect of a vertical ground plane (image plane) close to the dipole, and iii) the length of the antenna as it relates to the width of the pulse (pulse at half-amplitude is $\sim$2 ns). The latter two have been found to be the most important in influencing the pulse shape. The complications in this pulse shape have been considerably reduced by significantly lengthening the transmitting antenna. A distinct peak pulse may now be resolved; smaller undulations corresponding to reflections having long delay times (relative to that associated with the inter-antenna separation) are still present.

Current work is being directed toward further refining and simplifying the received waveform by moving the source dipole closer to the horizontal center of the underlying metal surface assembled in the laboratory. In this way it is expected to be less influenced by reflections from the vertical ground plane near which it lies. Such reflections are quite complicated since, although image theory applies, an image is associated with each frequency component of the radiated signal.

As a further check on the apparatus, the vertical-dipole transmitting element has been connected to the vertical ground plane of earlier studies[2,3] near which near which it lies, so that the antenna forms essentially a *short* circuit as opposed to an open circuit. In this way the pulse is reflected back with opposite polarity to that observed for the ungrounded case and produces a noticeable difference in the leading edge of the first maximum in the pulse waveform.

The second set of measurements in the aforementioned sequence is about to commence, namely, the study of vertical monopoles above salt water. This represents a transition to a half-space problem. The waveforms are expected to be quite similar to those obtained over the metal underburden (ground plane) discussed above. The ground-plane studies have thus been made to serve two purposes: i) to test the apparatus, and ii) to serve as a basis for comparison with the salt-water results.

In a separate study an investigation has been made of the effects of atmospheric noise on the lateral-wave propagation between submerged horizontal dipoles in the sea.[4] Calculations have been made for sea water with $\varepsilon_{1r} = 80$, $\sigma_1 = 4$ S/m. The vertical noise is for the worst-time conditions of summer-time for Eastern U.S.A. at 40°N latitude. Curves are shown for the vertical and horizontal noise components of the electric field at the surface, and the field strengths of the radial component $|E_{1\rho}|$ of the lateral-wave field generated by an infinitesimal horizontal electric dipole with unit moment in the sea at radial distances from $\rho = 1$ to 100 km. Similar curves are also presented for a practical antenna system with moment $I\Delta\ell = 100 \times 100 = 10^5$ A·m. The resulting signal-to-noise ratios have been plotted as functions of the radial range for $f = 1$, 10, 100 and 1000 kHz. These results infer useful communication to submarines using lateral waves limited by attenuated atmospheric noise for shallow depths. For greater depths, lower frequencies should provide more optimum signal-to-noise ratios.

References

1. H.M. Shen, R.W.P. King, and T.T. Wu, "The Dual-Measurement Procedure for Eliminating Systematic Interference," *IEEE Trans. Electromagn. Compatibil.* EMC-26, 14-18 (Feb. 1984).

2. M.F. Brown, R.W.P. King, and T.T. Wu, "Lateral-Wave Studies in a Model Lithosphere," *J. of Appl. Phys.* 53, 3387-3396 (May 1982).

3. M.F. Brown, R.W.P. King, and T.T. Wu, "Experiments on the Reflection of Lateral Electromagnetic Waves," *J. of Appl. Phys.* 55, 3927-3933 (June 1984).

4. J.T. deBettencourt, "Lateral Waves near the Air-Sea Boundary and Atmospheric Noise," *Proc. of the IEEE* 72, 1219-1221 (Sept. 1984).

IV.5 Theoretical and Experimental Studies of Lateral-Wave Propagation. J.M. Dunn and W.-Y. Pan, Contract N00014-84-K-0465; Research Unit 11 (former #10).

Current interest in the possibility of investigating the electrical properties of the earth beneath the ocean by electromagnetic means naturally leads to the problem of wave propagation in layered media. A realistic model of the earth's crust typically includes a layer of sediment followed by many layers of rock of various types. Lateral-wave propagation for such cases can be much more complicated since a different wave can travel in each of the rock regions and, at the same time, each of the waves is influenced by the neighboring regions. Geophysicists are interested in the electrical properties of these rock layers as well as their thicknesses and orientations.

The simplest multi-layered model that takes into account the presence of a highly conducting mantle region beneath a layer of rock is that of a horizontal dipole antenna located near a salt water-air interface with a perfectly conducting top plate above the air region. The salt water represents the ocean, the air region is the analog of the rock layer, and the top plate corresponds to the highly conducting mantle. A theoretical investigation of this problem has been carried out.[1-3] The theoretical expression for the radial electric field E_ρ is in the form of modes and may be obtained either directly from the integrals or from approximate perturbative methods. It is no coincidence that the expression for E_ρ is very similar to that for a waveguide since the air region is very much like a slab waveguide with a lossy wall at the air-water interface.

An experimental study of lateral-wave propagation in the presence of a top plate has also been completed.[1,2,4] As predicted by theory, the measured fields exhibit a waveguide-type behavior, i.e., the pattern is understandable in terms of modes. For the top plate at a height h above the water-filled tank of less than a half-wavelength, an exponential decay is observed with small superimposed oscillations due to side-wall reflections. For heights between a half and a full wavelength, another mode is observed which produces large oscillations in the pattern. As the height is increased further, more and more modes come into play, as expected.

A more realistic three-layer model consists of a semi-infinite water layer (Region 1), a sediment layer composed of a mixture of sand and water

(Region 2), and a semi-infinite rock layer (Region 3). A theoretical study of this configuration has been made.[1,2,5] An infinitesimal horizontal time-harmonic electric dipole is in Region 1 a distance d above the interface between Regions 1 and 2 ($z = 0$). Analytical expressions have been obtained for the electromagnetic fields in Region 1 near the interface, subject to the following restrictions: (1) Both d and z are small compared to a wavelength in the water, where d is the height of the transmitting dipole above the interface ($z = 0$) between Regions 1 and 2 and z is the height of the receiver; (2) the radial distance ρ from the dipole is large compared to z and d; and (3) the two parameters $\alpha = k_2/k_1$ and $\delta = k_3/k_2$ are small in magnitude, where k_j is the complex wave number of the j-th medium. These three criteria are satisfied nicely in practical cases. The three-layer solution looks very much like the Wu-King two-layer solution. The differences are: (1) there is a sediment term which represents the contribution from the wave traveling in the sediment layer; at distances and frequencies of interest, it is negligible; (2) there is a constant A which can change the magnitudes of the fields; and (3) the Fresnel integral now depends on a complicated constant ν. It is this greater complication that makes the solution interesting. Hopefully a means can be determined to exploit these differences and thereby determine not only the parameters of the rock region but also the thickness of the sediment layer.

Current work on this project is being devoted to modifying the experimental setup used in the top-plate measurements so that the more important case of air over a sheet of dielectric over water can be studied. All of the necessary equipment is available including the model tank, generator, receiver, and automated movable receiving probe. Construction of an intermediate layer using sheets of wallboard of different thicknesses is required. To begin with both the transmitting and receiving antennas will be located in the water just beneath the interface with the wallboard. The possibility of later locating the receiver in the wallboard is being considered. The wallboard will be separated from the water by a very thin sheet of plastic so that the amount of water absorbed by the wallboard can be controlled.

References

1. J.M. Dunn, "Electromagnetic Lateral Waves in Layered Media," Doctoral Dissertation, Harvard University, 1984.

2. J.M. Dunn, R.W.P. King, and T.T. Wu, "Lateral Waves and Their Use in Lithospheric Exploration," presented at the Workshop on Geomagnetic Properties of Continental Margins, Colorado School of Mines, Golden, Colorado, Apr. 29 - May 1, 1984. (Partial support by ONR Contract N00014-79-C-0419).

3. J.M. Dunn, "Effect of Perfectly Conducting Top Plate on Lateral-Wave Propagation," presented at the 1983 International IEEE/AP-S Symposium, Houston, TX, May 1983.

4. J.M. Dunn, "Experimental Study of Lateral-Wave Propagation with a Conducting Top Plate," presented at the 1984 International IEEE/AP-S Symposium, Boston, MA, June 1984.

5. J.M. Dunn, "Lateral Waves in Three-Layered Media," presented at the 1984 International IEEE/AP-S Symposium, Boston, MA, June 1984.

IV.6 Fields and Currents and Charges on Obstacles in a Parallel-Plate Simulator at Selected Frequencies and with Pulse Excitation. W.-Y. Pan, R.W.P. King, and T.T. Wu, Contract N00014-84-K-0465; Research Unit 11 (former #10).

The parallel-plate Harvard EMP simulator has been investigated during the past several years in order to acquire a deep understanding of its properties as a means to improve its quality for EMP testing. The research was first carried out in the frequency domain and was then extended to the time domain. The investigation of the parallel-plate simulator under pulse excitation was begun with a comprehensive experimental study and subsequent theoretical analysis of the simpler rhombic structure used as an EMP simulator excited by an impulse generator.[1,2] [These two papers received the 1983 Transactions Prize Paper Award of the IEEE Electromagnetic Compatibility Society in October 1984.] An experimental investigation of the metal-plate EMP simulator under pulse excitation was then conducted.[3-5] The conclusions are: (a) Formulas for the electric-field pulses in the working volume of the rhombic simulator show that these propagate quite smoothly and uniformly. They are continuously generated by current pulses in the rhombic conductors. (b) The incident pulse is everywhere independent of the terminating load. Since in an EMP test the incident pulse alone is of interest, the nature of the termination is irrelevant. (c) The nature of the electric-field pulses observed at successive locations in the metal-plate simulator is far from simple. Their structure can be understood in part by comparison with the corresponding pulses in the rhombic

simulator. Only slight mismatches between the pulse generator and the coaxial line and between this and the simulator suffice to transform a single pulse leaving the generator into a complex pulse sequence entering the simulator.

During this reporting period the work has continued with a study of the obstacle-simulator interaction under pulse excitation. The distributions of surface current and charge induced on a vertical metal cylinder by an electromagnetic pulse have been investigated experimentally in the Harvard parallel-plate EMP simulator.[6] Fourier transforms of the observed pulse shapes are taken in order to obtain distributions of the several frequency components on the surface. These are then compared with theoretical distributions calculated using Kao's method. The measured data are found to be in basically good agreement with those theoretical distributions induced by the sum of the incident and reflected pulses. Observed differences between measured and theoretical distributions for certain frequency components of the transverse current I_θ are probably due to coupling between the cylinder and the simulator top plate. A quantitative analysis of the interaction between the cylinder and the simulator is very interesting but difficult; it requires further study.

The measured current pulse sequences induced on the vertical cylinder described above have also been compared, in a separate paper,[7] with theoretically determined pulse shapes of current induced on an infinitely long conducting cylinder by an E-polarized electromagnetic pulse. For an E-polarized incident electromagnetic pulse with a nonzero direct component, the axially induced current pulse has an infinite direct component and the Fourier integration is divergent. In order to avoid this difficulty, the Laplace transform for the variable t is taken instead of the Fourier transform. After the inverse Laplace transform has been taken, the pulse shapes of the axial induced current can be expressed as the sum of only a few terms. The measured pulse sequences for the finite cylinder closely resemble, in its main features, those of the infinite cylinder but with a series of small reflected pulses added.

The experimental and theoretical investigation of the rhombic simulator under pulse excitation[1,2] indicated that the electromagnetic pulse in the working volume of the simulator is excited by the current in the wires near the source rather than that in the wires near the center of the simulator. This observation is somewhat different from that in the frequency domain. The same question must be asked for the parallel-plate simulator: Does the triangular

plate near the source also play the most important role in forming the electromagnetic pulse in the working volume of the parallel-plate simulator? To answer this question, the electromagnetic pulse has been evaluated in terms of the currents on the plates and the roles of the currents on different parts of the plates have been analyzed. A paper is now being written which clarifies the excitation mechanism of the parallel-plate EMP simulator. It is found that if the length of the parallel plate is short (i.e., close to the height h), the currents on the parallel plate contribute almost nothing to the electromagnetic pulse.

References

1. H.M. Shen, R.W.P. King, and T.T. Wu, "An Experimental Investigation of the Rhombic EMP Simulator under Pulse Excitation," *IEEE Trans. Electromagn. Compatibil.* EMC-25, 40-45 (Feb. 1983); 1983 trans. Prize Paper Award.

2. H.M. Shen, R.W.P. King, and T.T. Wu, "Theoretical Analysis of the Rhombic Simulator under Pulse Excitation," *IEEE Trans. Electromagn. Compatibil.* EMC-25, 47-55 (Feb. 1983); 1983 Trans. Prize Paper Award.

3. H.M. Shen, R.W.P. King, and T.T. Wu, "An Experimental Investigation of the Parallel-Plate EMP Simulator with Single-Pulse Excitation," *IEEE Trans. Electromagn. Compatibil.* EMC-25, 358-366 (Aug. 1983).

4. H.M. Shen, R.W.P. King, and T.T. Wu, "The Dual-Measurement Procedure for Eliminating Systematic Interference," *IEEE Trans. Electromagn. Compatibil.* EMC-26, 14-18 (Feb. 1984).

5. H.M. Shen, R.W.P. King, and T.T. Wu, "The Matching Between an EMP Simulator and the Pulse Generator," *IEEE Trans. Electromagn. Compatibil.* EMC-26, 4-13 (Feb. 1984).

6. Y.-Y. Pan, "An Experimental Investigation of the Distribution of Current and Charge Induced on a Tubular Conducting Cylinder by an Electromagnetic Pulse," *IEEE Trans. Electromagn. Compatibil.* (scheduled for May 1985 issue).

7. W.-Y. Pan, "The Theoretical Analysis of the Pulse Shapes of the Current on an Infinitely Long Conducting Cylinder Induced by an E-Polarized Electromagnetic Pulse," *IEEE Trans. Electromagn. Compatibil.* (submitted for publication).

IV.7 Arrays of Antennas Along Curved Lines. T.T. Wu, Contract N00014-84-K-0465 and DOE Grant DE-FG02-84ER40158; Research Unit 11 (former #10).

Over fifty years ago, Fermi invented his method of pseudopotentials to study nuclear scattering as described by the three-dimensional Schrödinger equation. It is clearly most desirable to extend this method to radiation problems as described by Maxwell's equation. Unfortunately, there is a rigorous mathematical theorem for operators in Hilbert space that such an extension is impossible.

An intermediate problem between those of nuclear physics and electromagnetic theory is described by the Schrödinger equation in five dimensions. It was found[1] that the rigorous mathematical theorem can be circumvented, the key point being the replacement of the Hilbert space by the Pontrjagin space. With this point understood, the method of Fermi pseudopotentials has been generalized to antenna arrays.[2] So far only very simple arrays have been treated, and the other cases remain to be worked out (see p. 304 of ref. 2).

References

1. A. Grossmann and T.T. Wu, "Fermi Pseudopotential in Higher Dimensions," *J. of Math. Phys.* 25, 1742 (1984).

2. T.T. Wu, "Fermi Pseudopotentials and Resonances in Arrays," in *Resonances-Models and Phenomena*, S. Albeverio, L.S. Ferreira, and L. Streit, eds. pp. 293-306 (Springer-Verlag, New York, 1984).

IV.8 Solitary Electromagnetic Pulses with Slow Decay. T.T. Wu and R.W.P. King, Contract N00014-84-K-0465 and DOE Grant DE-FG02-84ER40158; Research Unit 11 (former #10).

In a recent paper by J.N. Brittingham,[1] mathematical formulations are developed for "new, three-dimensional packet-like solutions to the free-space Maxwell's equations." These solutions are further characterized as "real, nonsingular, continuous functions which propagate in a straight line at light velocity. They remain focused for all time." It was subsequently shown by Bélanger[2] that a whole family of packet-like solutions of the homogeneous wave equation can be derived that includes Brittingham's form as a special case.

Brittingham and Bélanger both observed that pulses of the type formulated, while satisfying Maxwell's equations, carry infinite energy so that they are physically unrealizable. In order to overcome this difficulty, Brittingham[1] supplemented his three-dimensional wave-packet by preceding and following surfaces of discontinuity which served to keep the energy associated with the packet finite. Work in this area at Harvard began with the determination[3] that these bounded pulses of Brittingham no longer satisfy Maxwell's equations across the surfaces of discontinuity and are therefore not physically meaningful. Current research is concerned with the possibility of generating electromagnetic pulses which, while not "focused for all time" like Brittingham's, nevertheless propagate in a manner such that the energy associated with them decreases with the radial distance R much more slowly than as R^{-2}. The justification for the belief that this may be realizable comes from recent advances in particle physics. In particular, it is learned from this work that, even for extremely short wavelengths, a logarithmic dependence of such quantities as the total cross-section on the wavelength can, and does, occur. In the specific formulation proposed recently,[4] it is found that the energy received by a given detector must approach zero as it is moved further and further away from the pulse-generating antenna. However, this approach to zero can be much slower than given by the form R^{-2} for an outward-traveling spherical wave. Such cases of slow decrease are referred to as electromagnetic missiles. Another way of stating the result is that the product of the following two quantities can approach zero as slowly as one wishes: (1) the energy transmitted per unit area of receiver, and (2) the total area of the receiver. Examples are constructed when either one, but not both, of these quantities remains finite at infinite distance. Since the rate of decrease with distance of electromagnetic missiles can be very slow and they have the advantage of moving with the velocity of light, they have important possible applications.

References

1. J.N. Brittingham, "Focus Wave Modes in Homogeneous Maxwell's Equations: Transverse Electric Mode," *J. of Appl. Phys.* 54, 1179-1189 (1983).

2. P.A. Bélanger, "Packetlike Solutions of the Homogeneous-Wave Equation," *J. Opt. Soc. of Amer.* A1, 723-724 (July 1984).

3. T.T. Wu and R.W.P. King, "Comment on 'Focus Wave Modes in Homogeneous Maxwell's Equations: Transverse Electric Mode'," *J. of Appl. Phys.* 56, 2587-2588 (Nov. 1984).

4. T.T. Wu, "Electromagnetic Missiles," *J. of Appl. Phys.* (accepted for publication).

IV.9 Advanced Introduction to Electromagnetic Theory and Its Applications.
R.W.P. King and M. Owens, and S. Prasad Hinchey of Northeaster University, Contract N00014-84-K-0465; Research Unit 11 (former #10).

The manuscript for a new introductory book on electromagnetic theory and its applications has been completed and is in press by Prentice-Hall.[1] The foundations of electromagnetism are presented in the first six chapters in a manner following that in King's *Fundamental Electromagnetic Theory*--which is now out of print. Applications begin with a chapter on the scattering and diffraction of plane waves by a half-plane and continue with chapters on antennas, electric circuit theory, transmission-line theory, the insulated antenna, the theory of metal waveguides, waves along dielectric rods with reference to optical fiber transmission, and electromagnetic surface waves along boundaries. The presentation stresses the physical interpretation of the mathematical symbolism and the basic unity of the theory. The applications are arranged with increasing difficulty as logical continuations of the theory. They deal specifically with problems of continuing and current interest.

Reference

1. R.W.P. King and S. Prasad, *Fundamental Electromagnetic Theory and Applications*, Prentice-Hall (in press).

V. SIGNIFICANT ACCOMPLISHMENT REPORT

V.1 X-Ray Reflectivity Measurement of the Structure of the Surface of Water. A. Braslau, A. Weiss, J. Als-Nielsen,* and P.S. Pershan, Contracts N00014-84-K-0465, NSF DMR-82-12189, NSF DMR-83-16979, and NSF INT-83-11841; Research Unit 3.

During this report period we made the first measurement of the x-ray reflectivity of the surface of water. The angular dependence of the reflectivity is theoretically expected to follow the following law:

$$R(\theta) = RF(\theta)\exp[-(Q^2)\sigma^2$$

where $RF(\theta)$ is the reflectivity calculated from the Fresnel law of optics on the assumption of a sharp flat surface between air and the known dielectric constant of water at 1.54 Angstroms; $Q = (4\pi/\lambda)\sin(\theta)$; and σ is the mean square roughness of the surface. A simple model attributing the surface roughness to thermally excited capillary waves predicts $\sigma = (kT/4\pi\gamma)\int d^2q/q^2$ where γ is the surface tension of water and the limits on the integral depend on the spectrometer resolution and the molecular dimensions. The data agrees with this form and obtains a value for σ of 2.8 while this model obtains 3.2. The dependence on $1/\gamma$ is confirmed by our recent measurements on CCl_4. Although there has been considerable theoretical research into the surface roughness of simple liquids, this is the first measurement on the molecular length scale.

*This project was done in collaboration with Als-Nielsen. All his support as well as the experimental facilities at the synchrotron lab in Hamburg, Germany were provided by the Risø National Laboratory of Denmark.

V.2 Observation of Chaos in Josephson Junctions Driven at Far-Infrared Frequencies. Q. Hu, M. Iansiti, O. Liengme, J.U. Free, and M. Tinkham, Contracts N00014-84-K-0465 and N00014-83-K-0383; Research Unit 4 (former #2).

In last year's report, we described our success in demonstrating that responsivities near the quantum limit (one electron per photon) could be obtained in superconducting tunnel junctions operating in the far-infrared (FIR) spectral region. The major difficulty in pursuing this further in the direction of practical devices was that these experimental junctions were fabricated from soft metals (Sn and Pb) which made them unable to withstand the strains associated with repeated cycling between room temperature and helium temperature. To address this problem, we organized a collaboration with Dr. L.N. Smith, then of the Sperry Research Laboratories, in which he fabricated some devices using the SNAP (Selective Niobium Anodization Process) process. Apart from the radically different material and fabrication method, the configuration of these devices was similar to those reported earlier, having broadly resonant half-wave thin-film antennas and a junction area of order 1 μm^2. Because of their lower resistance, larger dielectric constant of the barrier, and somewhat larger physical size, coupling into these devices was not quite as effective as with the home-made Sn-Pb junctions, but preliminary experiments showed that Josephson steps could be induced.[1] Moreover, because of the lower resistance, noise rounding effects were minimal compared to those in the higher-resistance Sn-Pb junctions. The sharper resulting features should be superior for detection purposes, which depend on these extreme nonlinearities.

In the process of exploring the properties of these junctions, we discovered that merely reducing the FIR laser frequency from 604 GHz to 419 GHz (or to 245 GHz) resulted in observation of I-V curves of an entirely different character than those seen before, and so thoroughly understood; we attribute[2] these radical changes to the onset of "chaos" in the driven motion of the junction. The hallmarks observed are: extremely high levels of low-frequency noise, subharmonic step structures even when adjacent integer steps are missing, and meandering voltage levels in the I-V curve on otherwise well-defined and flat steps. Moreover, these effects are most prominent when the FIR drive frequency is close to the Josephson plasma frequency (estimated at 420 GHz in these junctions), as is expected from computer simulation studies of chaos.

The low-frequency noise levels in the chaotic regions can be as large as the equivalent of 10^{11}K thermal noise at 100 Hz. Further measurements of the power spectrum show that it falls off as $1/f^{\alpha}$ at higher frequencies, where α varies from 1 to 4, and may depend on the levels of dc bias and laser drive power. On the basis of our simulations, we suggest that although the noise *levels* may be qualitatively similar in different operating points, the fundamental origins may involve different chaotic mechanisms, such as period doubling cascades, intrinsic intermittency, and noise-induced intermittency.

One region we have studied particularly closely is that at the first onset of finite dc voltage, in which the system appears to be intermittently shifting between a zero-step and 2/3 step regime with a "1/f" spectrum. Our computer simulations (on a VAX) show that the "basins of attraction" for these two steps are extremely complex in form, separated by a boundary having a "fractal" dimension which depends on dc bias level and can grow almost to 2 (at which point the boundary would fill the entire phase plane). The experimental noise level shows a dependence on bias current that closely parallels this computed fractal dimension, qualitatively confirming the notion of Grebogi, et al.[3] that these fractal dimensions imply a sensitivity to initial conditions (and hence noise) which diverges as the dimension approaches 2. Effectively, shot noise due to the discreteness of the electronic charge is amplified enormously to generate immense 1/f-type noise. This work is the first of which we are aware in which data on a real physical system has confirmed these implicit consequences of the fractal basin boundary. The practical significance of this work is that the many routes to chaos must be understood so that this source of extraordinary noise levels can be avoided in the design of actual devices.

References

1. W.C. Danchi, F. Habbal, J.U. Free, M. Tinkham, and L.N. Smith, Proc. 1984 Appl. Supercond. Conf., to appear.

2. Qing Hu, J.U. Free, M. Iansiti, O. Liengme, and M. Tinkham, Proc. 1984 Appl. Supercond. Conf., to appear.

3. C. Grebogi, S.W. McDonald, E. Ott, and J.A. Yorke, *Phys. Lett.* 99a, 415 (1983).

V.3 The Application of Electromagnetic Surface Waves to Geophysical Prospecting from the Surface of the Earth. T.T. Wu and R.W.P. King; Research Unit 11 (former #10).

An important application of electromagnetic waves is in remote sensing, notably in the search for underground regions containing oil or ore. A convenient and useful procedure makes use of a fixed insulated transmitting dipole and a movable receiving antenna both on the surface of the earth. How is the field measured by the receiver related to a buried object? A quantitative answer to this question is essential to an understanding and exploitation of the method and the correct interpretation of measured data. This has now been provided in the form of a complete theoretical analysis and a significant set of preliminary measurements in a model tank.

The first step in the analysis is the determination of the electromagnetic field incident on a buried object. This is not the field that travels directly through the earth from the transmitter to the scattering obstacle or boundary but a lateral wave that proceeds along the surface in the air to a point above the obstacle and then vertically down to it. Recent researches have provided simple and accurate formulas for the six components of this field.[1-5] They have been determined specifically for a horizontal dipole over the earth.[6] Significantly, the largest components of this field are the radial electric ($E_{1\rho}$) and transverse magnetic ($B_{1\phi}$) in the direction *along the axis* of the transmitting antenna. In order to obtain a simple and accurate solution that could be used to verify an experiment in a model tank, the first choice of buried object to be located was an insulated cylindrical conductor in salt water. Complete calculations of the incident, scattered, and total fields over a wide area over the surface of the earth above the submerged cylinder with its depth as parameter show a clear, readily interpreted interference pattern directly over the cylinder.[7] The location, shape and orientation of the cylinder are clearly determined as sharp rises or dips in the total field. This interference pattern consists of sharp increases in the field over the cylinder when its depth is such that the scattered and incident fields are in phase at the receiver, or equally sharp decreases when the incident and scattered fields are out-of-phase.

No measurements of the scattered field of a submerged metal cylinder have yet been made. However, measurements have been carried out by Bansal[8]

of the corresponding patterns generated by a submerged circular metal disk. These indicate the same type of interference above the edges of the disk. To complete the study, measurements should be made for the submerged cylinder and the theory developed for the submerged disk. Results to date fully confirm and illuminate the method and describe the conditions for its optimum application. An even broader scope could be achieved with theoretical studies and sets of measurements for a number of different scattering regions with properties other than those of conductors.

References

1. T.T. Wu and R.W.P. King, "Lateral Waves: A New Formula and Interference Patterns," *Radio Science* 17, 521-531 (May-June 1982).

2. T.T. Wu and R.W.P. King, "Lateral Waves: New Formulas for $E_{1\phi}$ and E_{1z}," *Radio Science* 17, 532-538 (May-June 1982); Correction, vol. 19, 1422, (Sept.-Oct. 1984).

3. R.W.P. King and T.T. Wu, "Lateral Waves: Formulas for the Magnetic Field," *J. of Appl. Phys.* 54, 507-514 (Feb. 1983); Erratum, vol. 56, 3365 (Dec. 1984).

4. R.W.P. King, "New Formulas for the Electromagnetic Field of a Vertical Electric Dipole in a Dielectric or Conducting Half-Space Near Its Horizontal Interface," *J. of Appl. Phys.* 53, 8476-8482 (Dec. 1982); Erratum, vol. 56, 3366 (Dec. 1984).

5. R.W.P. King, "The Wave Antenna for Transmission and Reception," *IEEE Trans. Antennas Propagat.* AP-31, 956-965 (Nov. 1983).

6. R.W.P. King, "The Scattering of Lateral Waves by Buried or Submerged Objects. I. The Incident Lateral-Wave Field," *J. of Appl. Phys.* (scheduled for 1 March 1985 issue).

7. R.W.P. King, "The Scattering of Lateral Waves by Buried or Submerged Objects. II. The Electric Field on the Surface Above a Buried Insulated Wire," *J. of Appl. Phys.* (scheduled for 1 March 1985 issue).

8. R. Bansal, "Electromagnetic Scattering from Conducting Objects Immersed in a Dissipative Half-Space," presented at the National Radio Science Meeting, Boston, MA, June 1984.

END

FILMED

6-85

DTIC